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Koga et al.

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(54) **ANTENNA DEVICE AND WIRELESS COMMUNICATION DEVICE**

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H01Q 5/10 (2015.01)

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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,439,917 B2* 10/2008 Harano H01Q 1/243 343/702

2004/0008146 A1 1/2004 Ikegaya et al.
(Continued)

FOREIGN PATENT DOCUMENTS

CN 102983405 A 3/2013
EP 2 784 873 A1 10/2014
(Continued)

OTHER PUBLICATIONS

International Search Report issued in corresponding PCT Application No. PCT/JP2018/012696, dated Jun. 5, 2018.

(Continued)

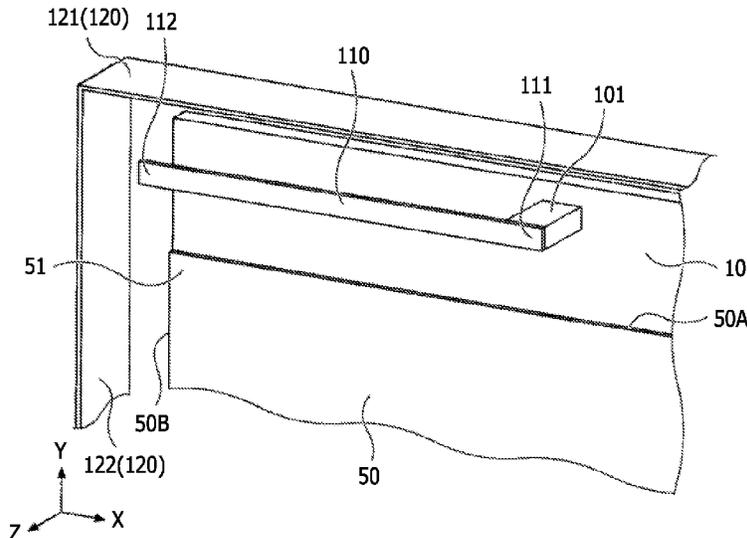
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(57) **ABSTRACT**

An antenna device includes: a ground plane which has an edge side; a metal member arranged along the edge side of the ground plane; a first connection line which couples the metal member and the ground plane; a second connection line which couples the metal member and the ground plane; and a power feeding element which has a power feeding point, extends along the metal member from the power feeding point between the first connection line and the second connection line, and is electromagnetic-field-coupled to the metal member.

14 Claims, 24 Drawing Sheets



(51) **Int. Cl.**

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H01Q 7/00 (2006.01)
H01Q 5/378 (2015.01)
H01Q 5/371 (2015.01)
H01Q 9/42 (2006.01)
H01Q 1/48 (2006.01)

FOREIGN PATENT DOCUMENTS

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 (2013.01); **H01Q 9/04** (2013.01); **H01Q 9/42**
 (2013.01)

EP 3 043 419 A1 7/2016
 JP 2004-048119 A 2/2004
 JP 2007-180656 A 7/2007
 JP 2009-165003 A 7/2009
 JP 2010-028521 A 2/2010
 JP 2014-200088 A 10/2014
 WO WO 2012/144197 A1 10/2012
 WO WO 2014/064786 A1 5/2014
 WO WO 2014/068192 A1 5/2014

(56)

References Cited

U.S. PATENT DOCUMENTS

2004/0196189 A1* 10/2004 Yeh H01Q 9/30
 343/700 MS
 2013/0057437 A1 3/2013 Chiu et al.
 2014/0132457 A1* 5/2014 Galeev H01Q 1/243
 343/702
 2014/0292590 A1 10/2014 Yoo et al.
 2014/0347229 A1 11/2014 Chen et al.
 2015/0048979 A1* 2/2015 Asrani H01Q 1/521
 343/702
 2015/0084817 A1* 3/2015 Yong H01Q 5/335
 343/702
 2015/0207211 A1 7/2015 Martiskainen et al.
 2015/0270610 A1 9/2015 Kodama

OTHER PUBLICATIONS

Written Opinion of the International Searching Authority issued in corresponding PCT Application No. PCT/JP2018/012696, dated Jun. 5, 2018. (with Partial Translation).
 Chinese Office Action issued by the Chinese Patent Office in corresponding Chinese Application No. 201880003596.7, dated Jul. 20, 2020.
 The Second Office Action issued from the State Intellectual Property Office of People's Republic of China in counterpart Application No. 201880003596.7, dated Feb. 20, 2021.

* cited by examiner

FIG. 2

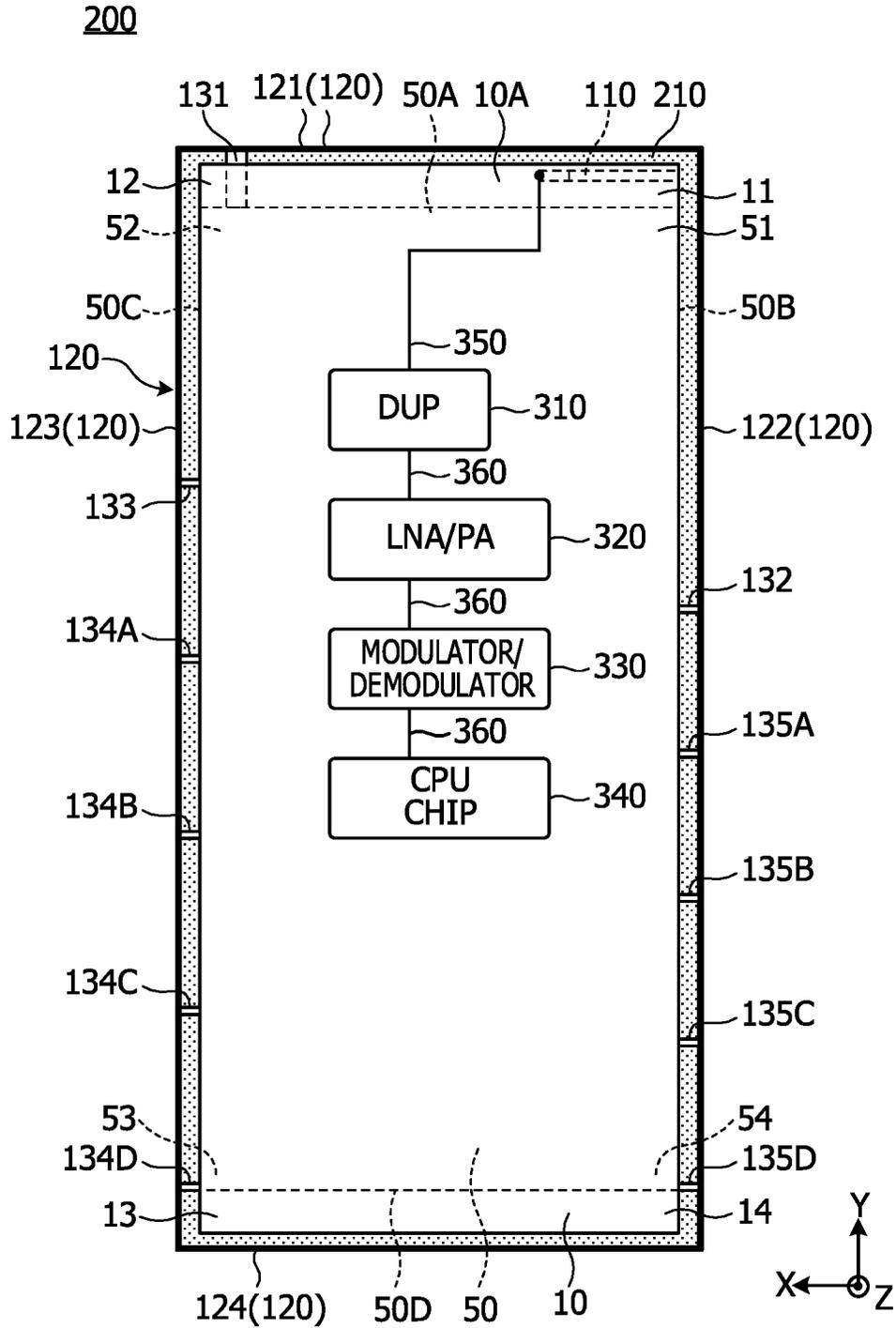


FIG. 3

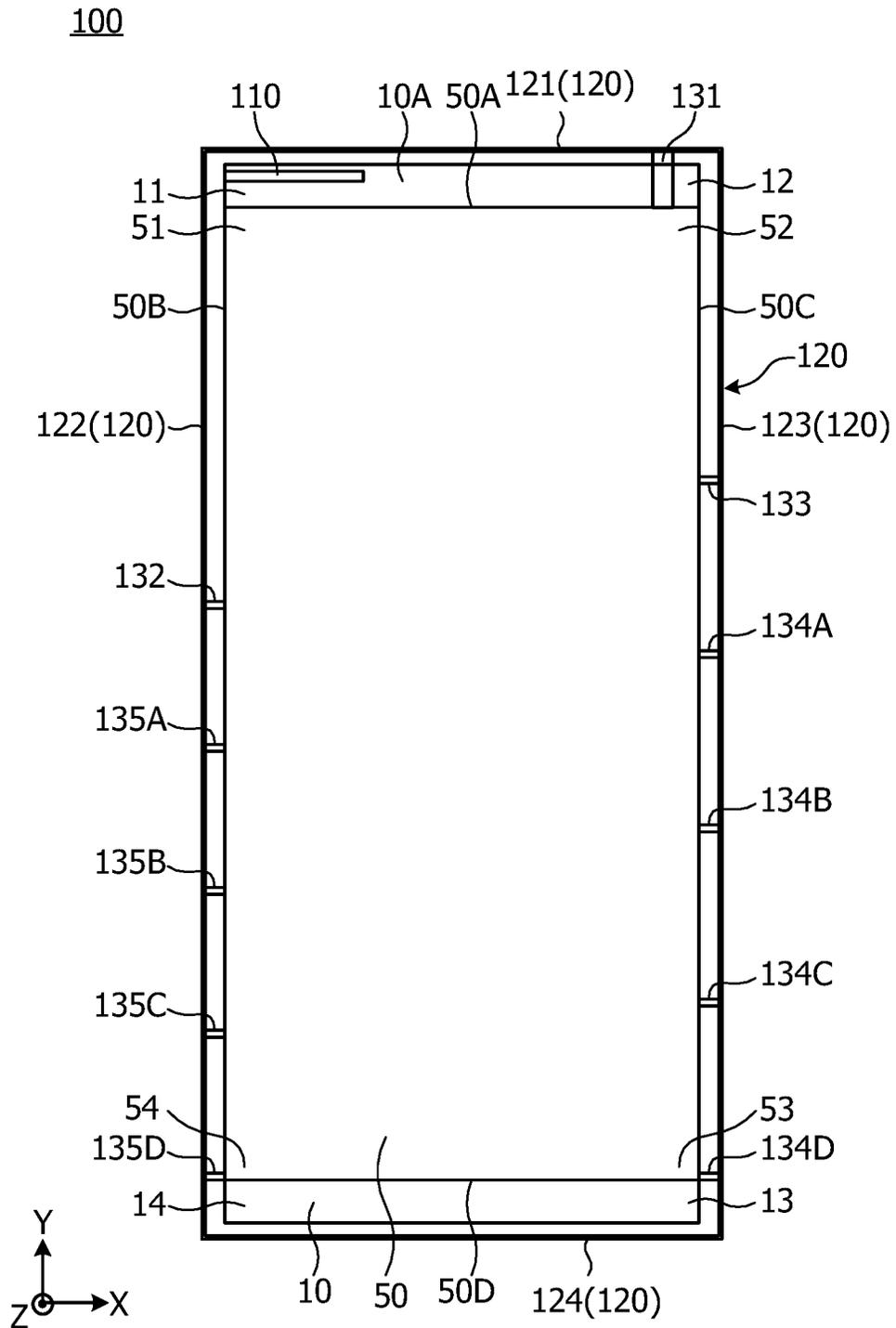


FIG. 4

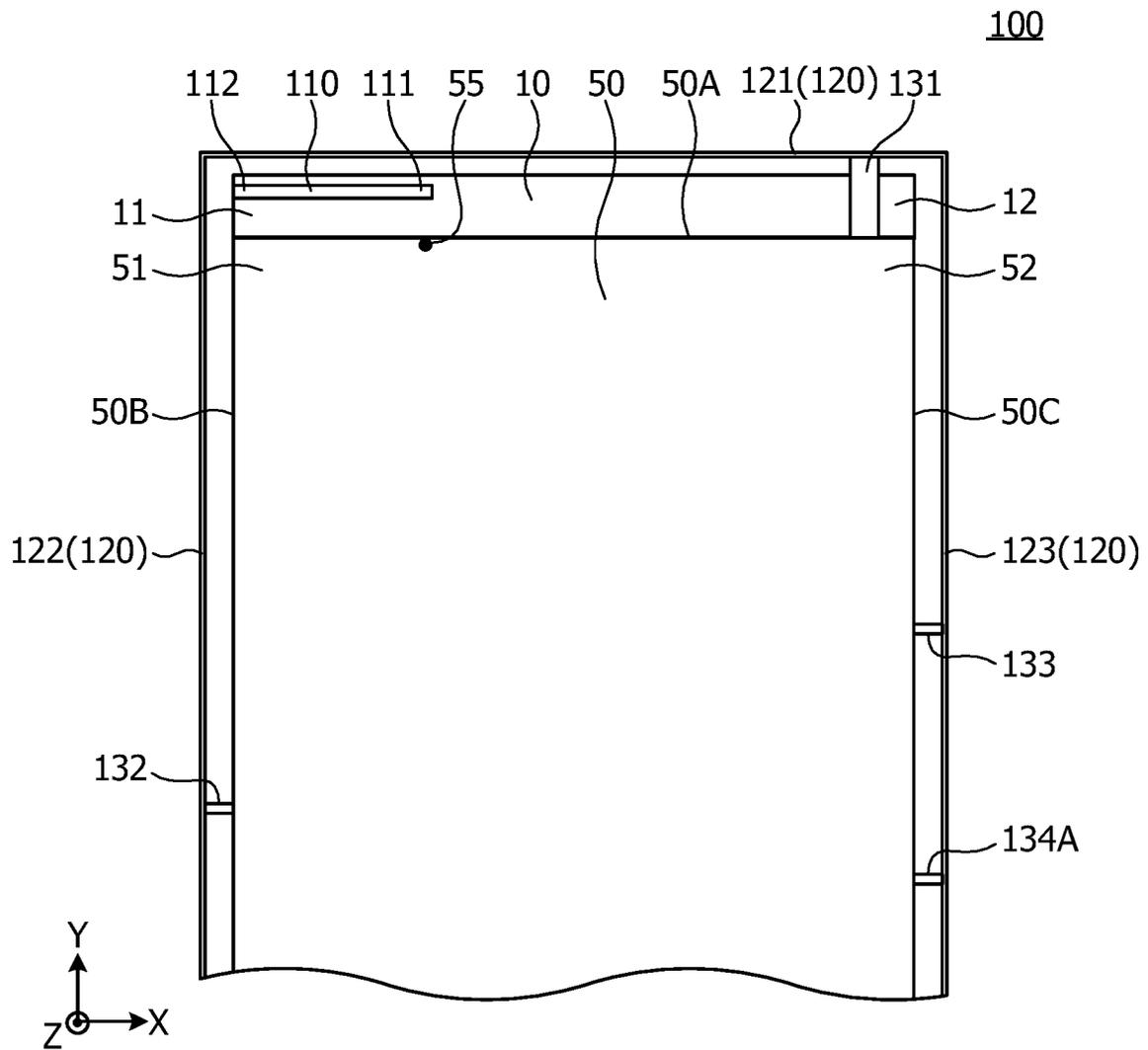


FIG. 5

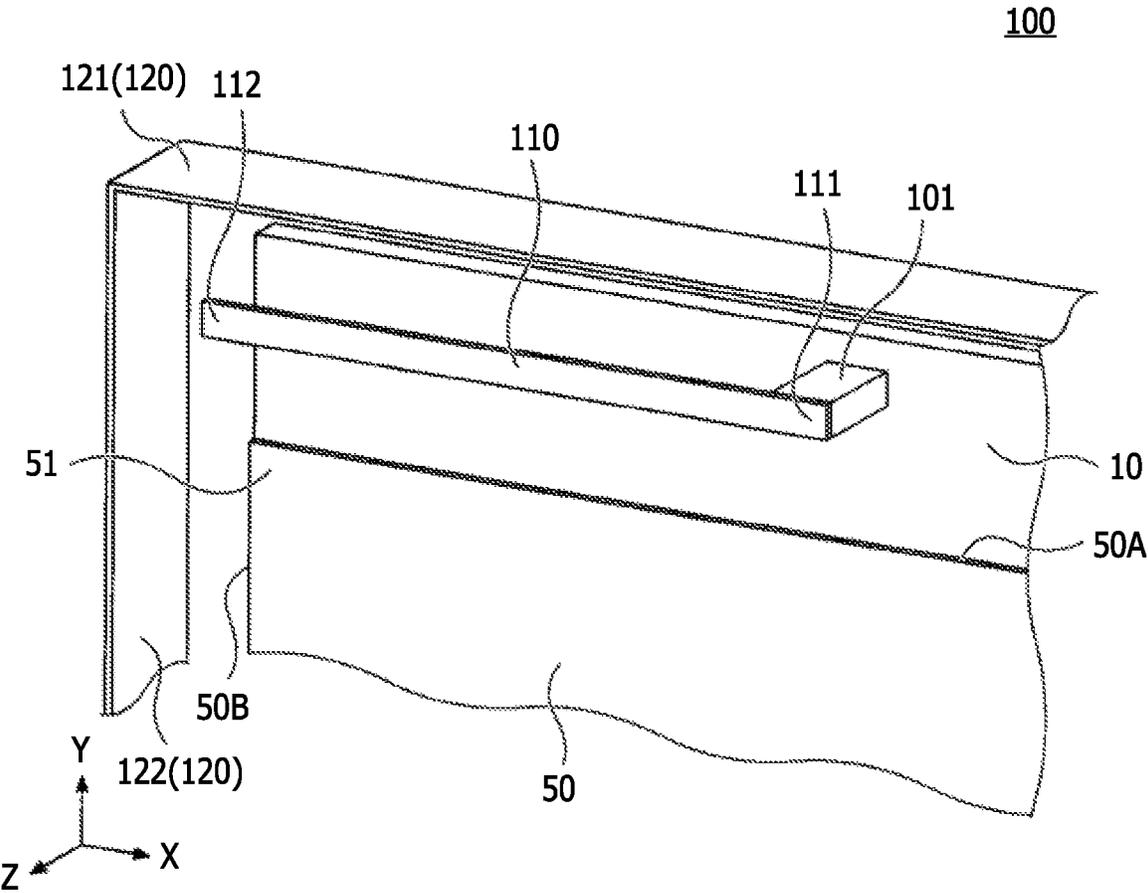


FIG. 6

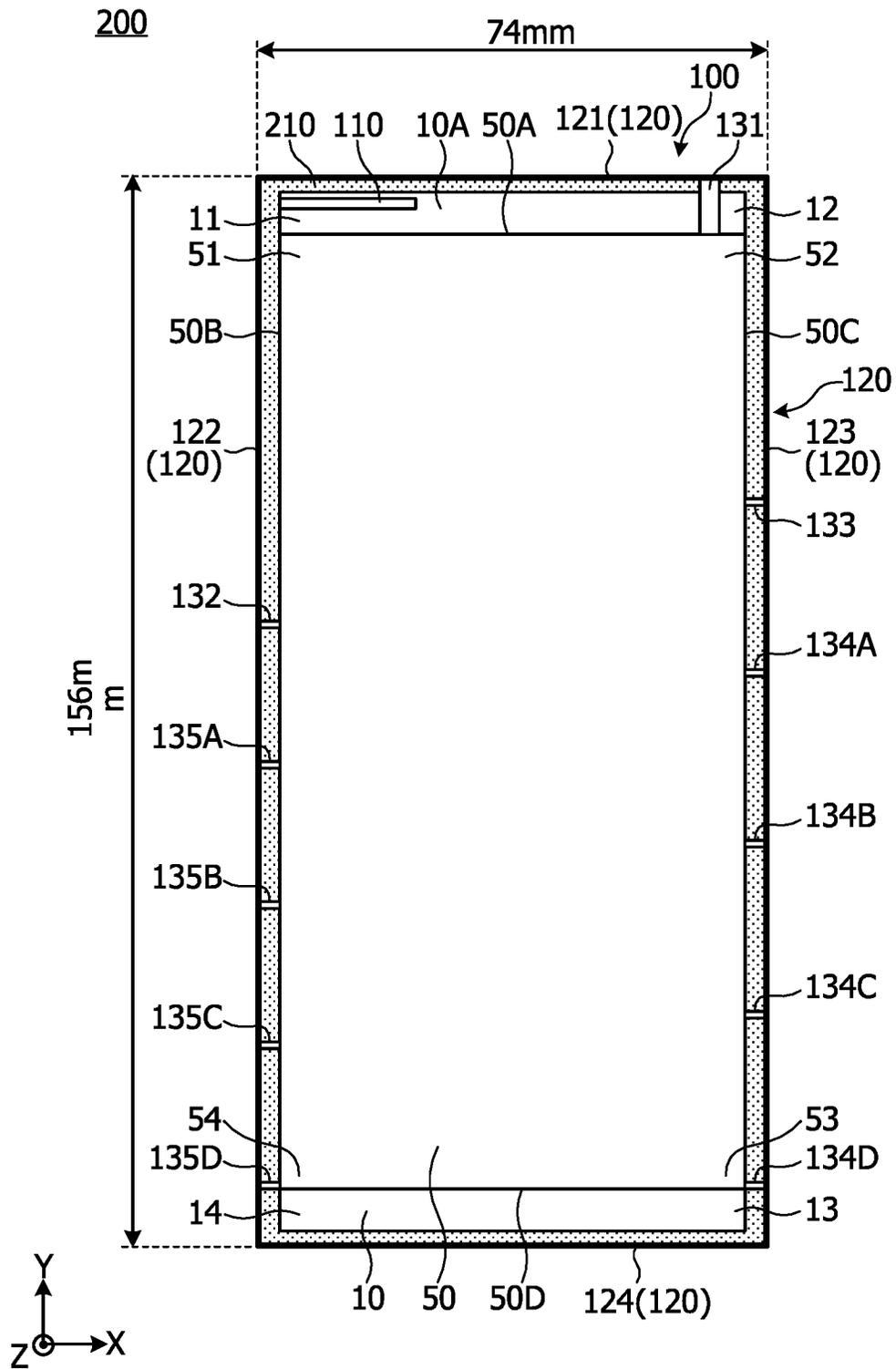


FIG. 7

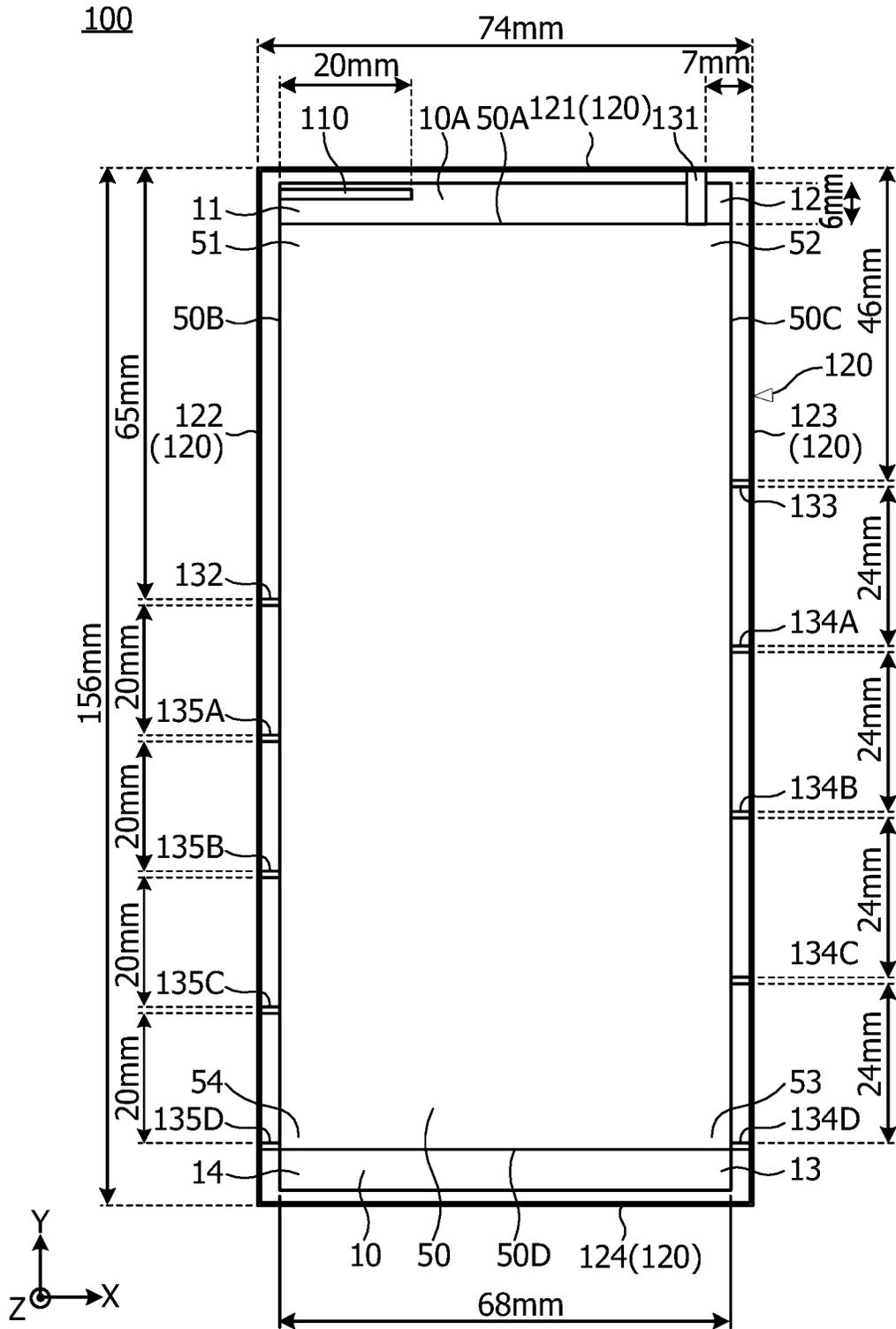


FIG. 8

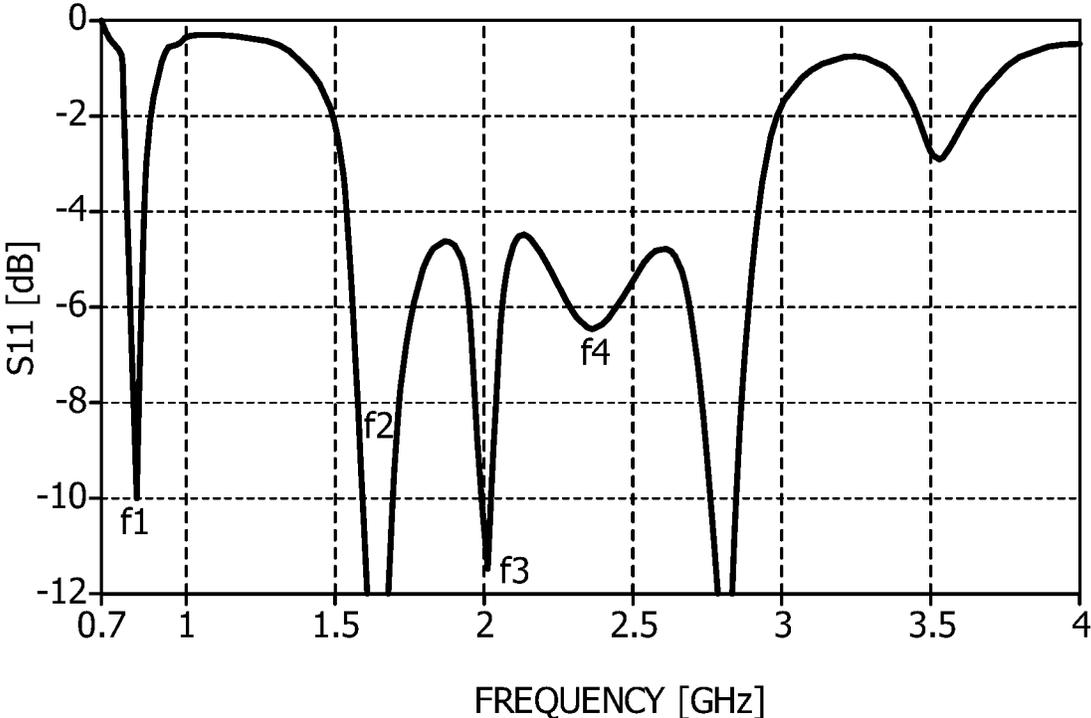


FIG. 9

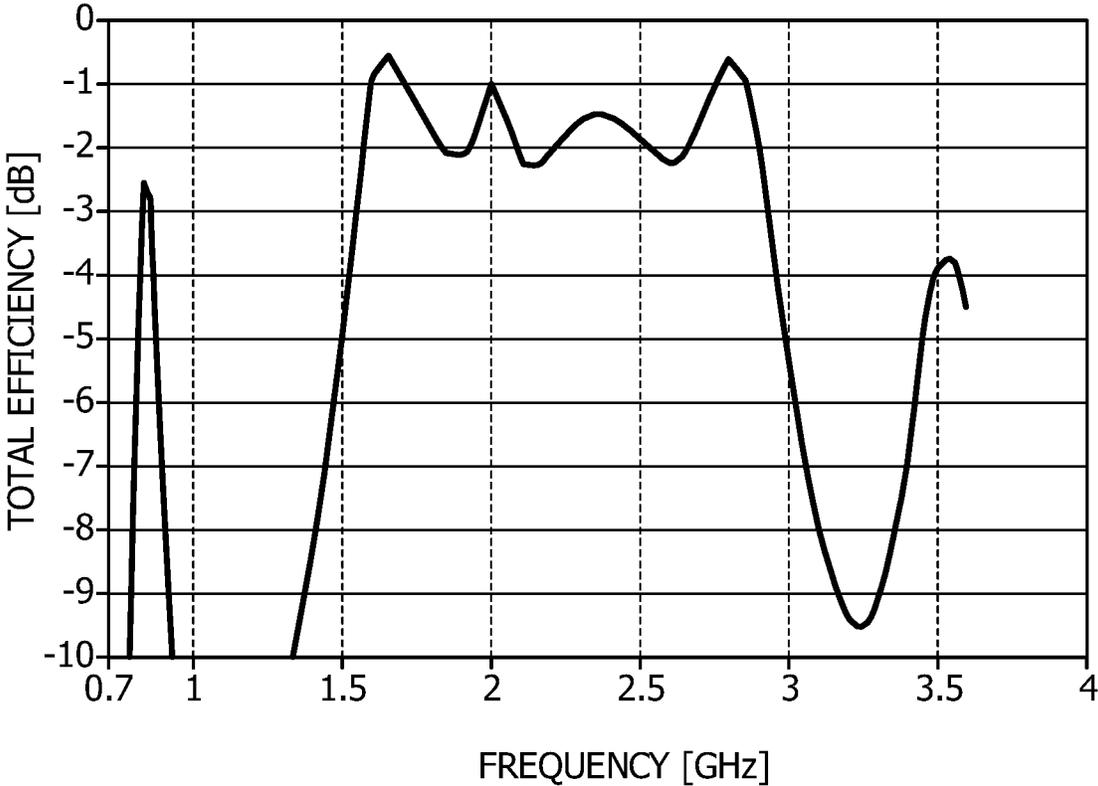
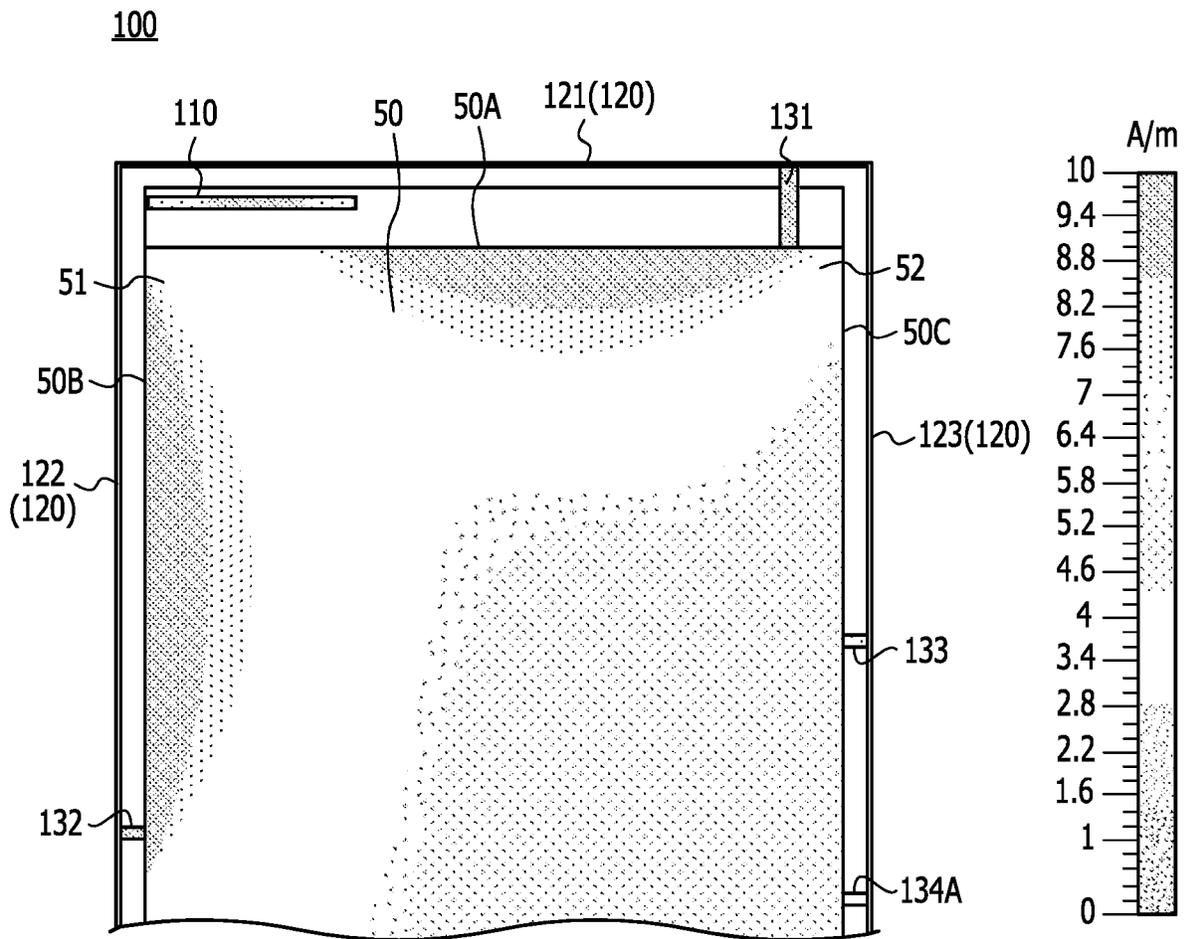
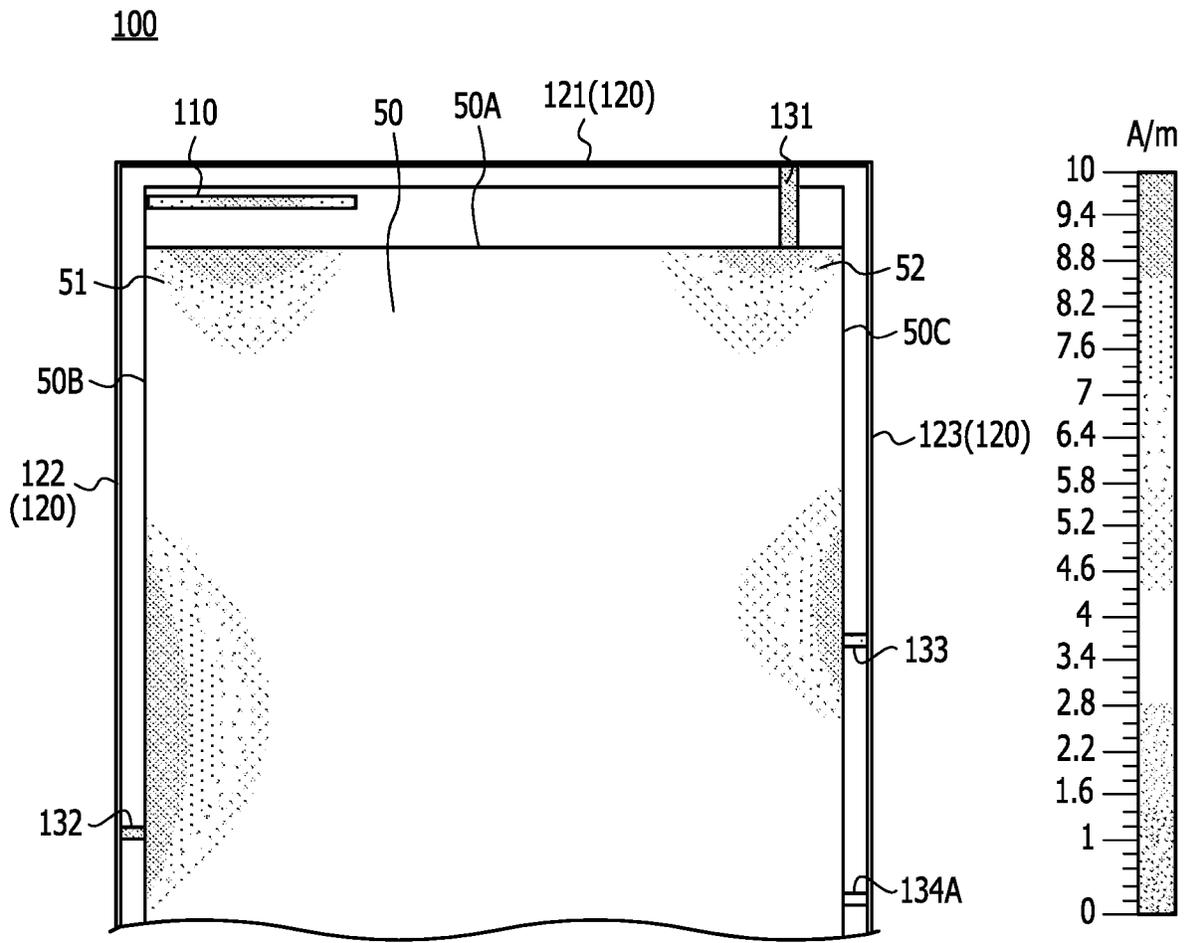


FIG. 10



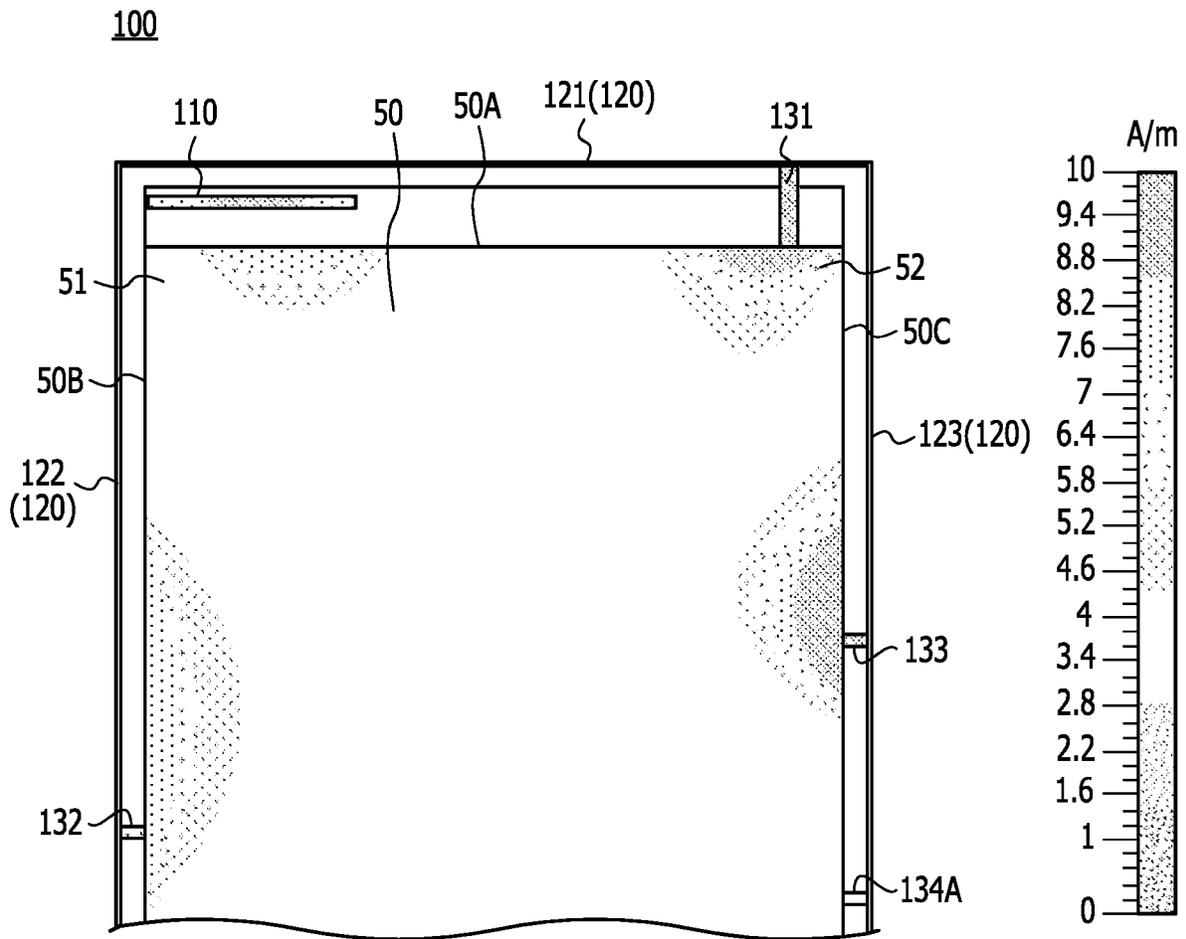
CURRENT DISTRIBUTION AT f1 (0.85 GHz)

FIG. 11



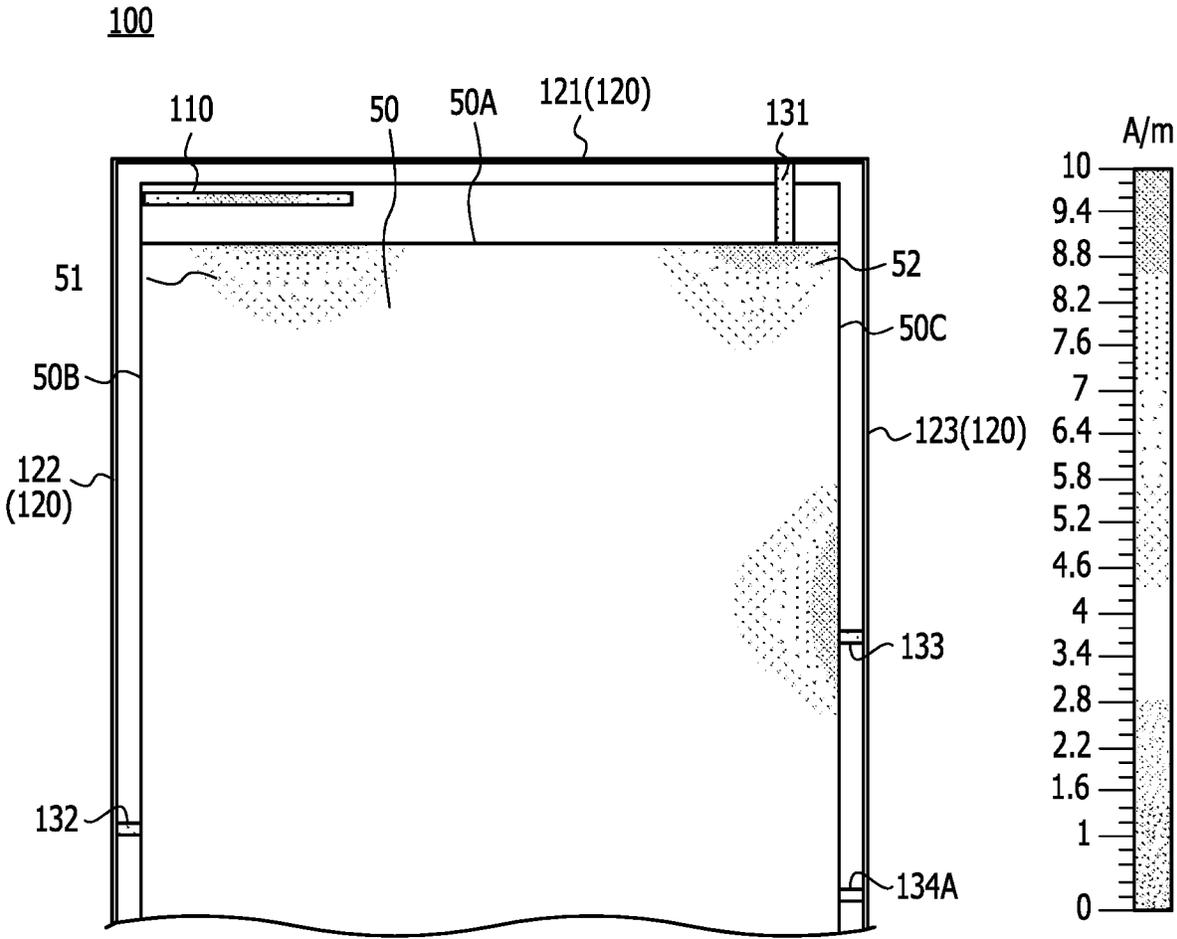
CURRENT DISTRIBUTION AT f2 (1.65 GHz)

FIG. 12



CURRENT DISTRIBUTION AT f3 (2.0 GHz)

FIG. 13



CURRENT DISTRIBUTION AT f4 (2.4 GHz)

FIG. 14

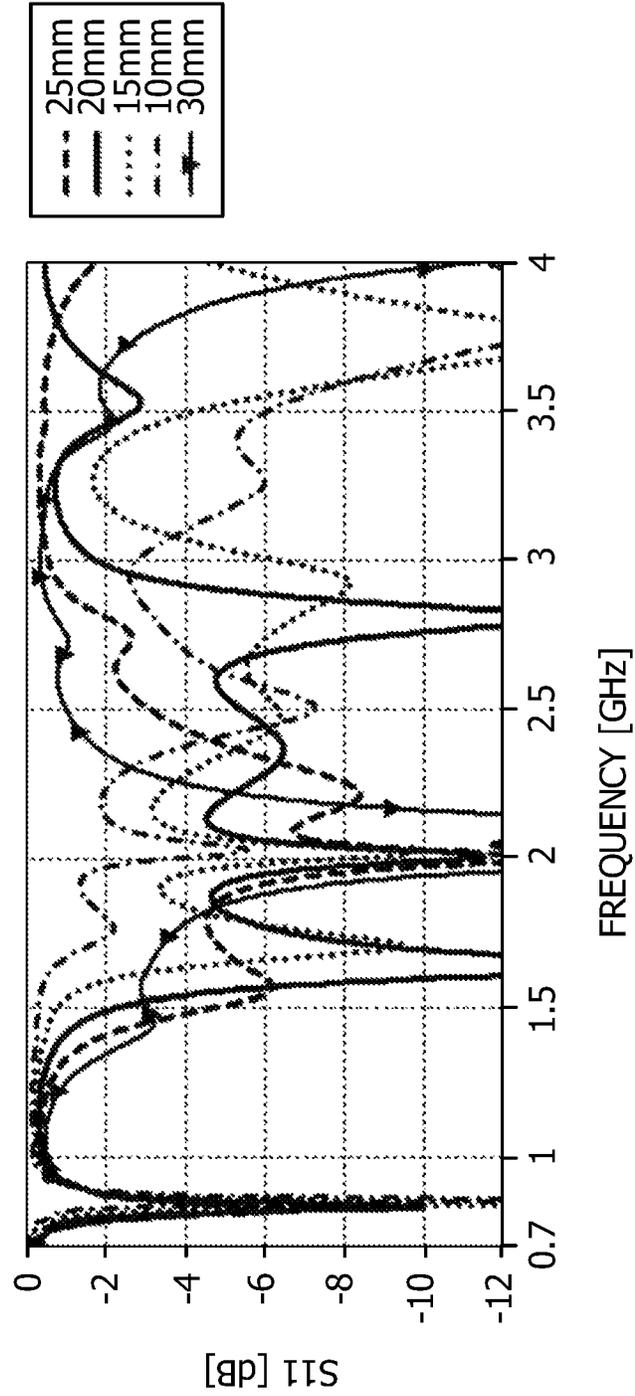
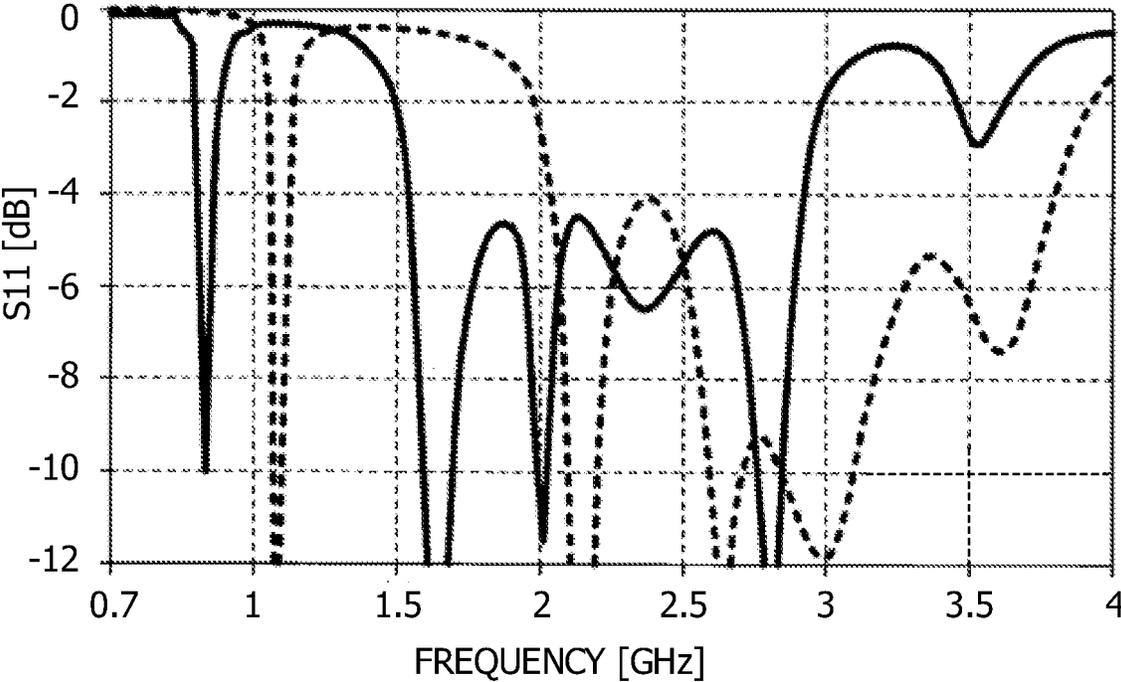


FIG. 15



— WITH HOUSING
- - - WITHOUT HOUSING

FIG. 16

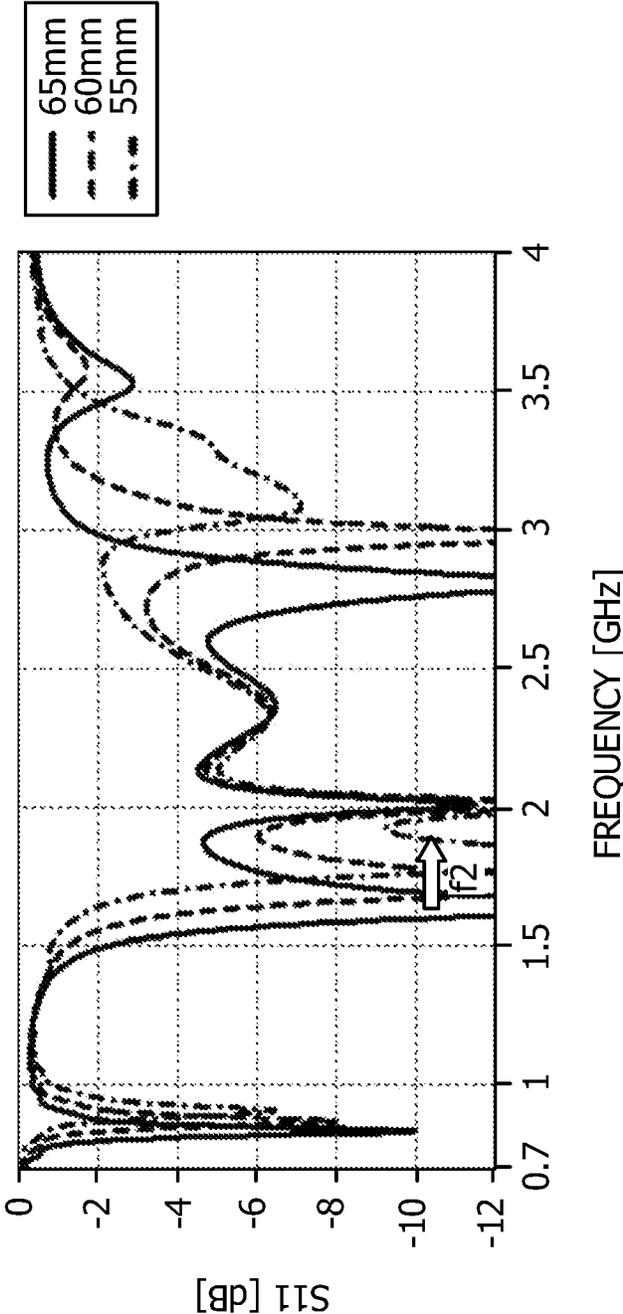


FIG. 17

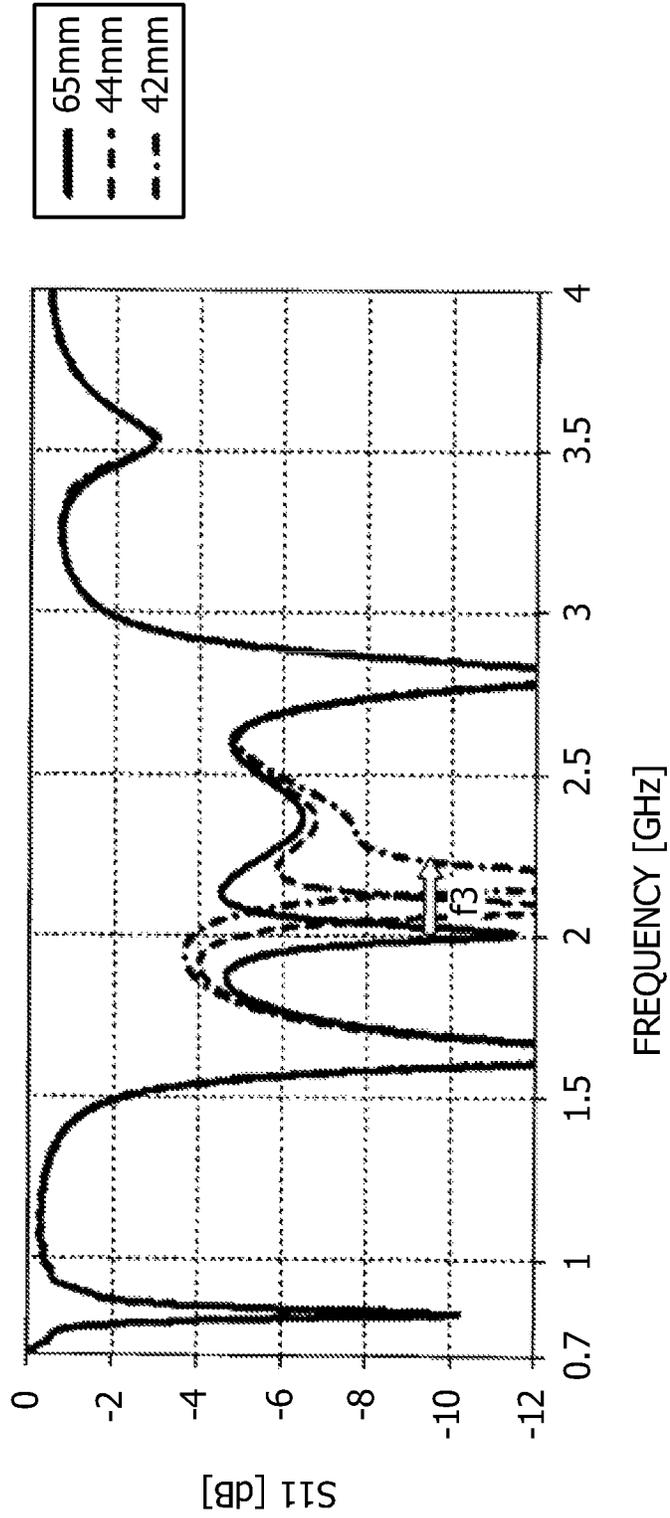


FIG. 18

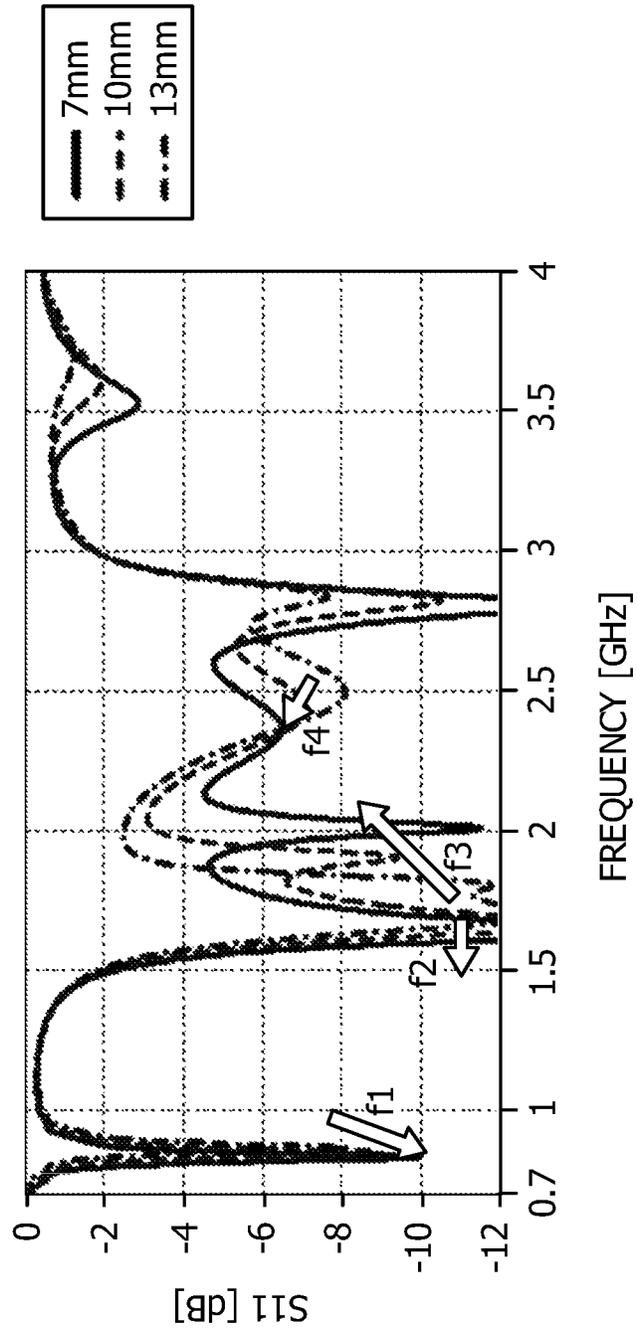


FIG. 19

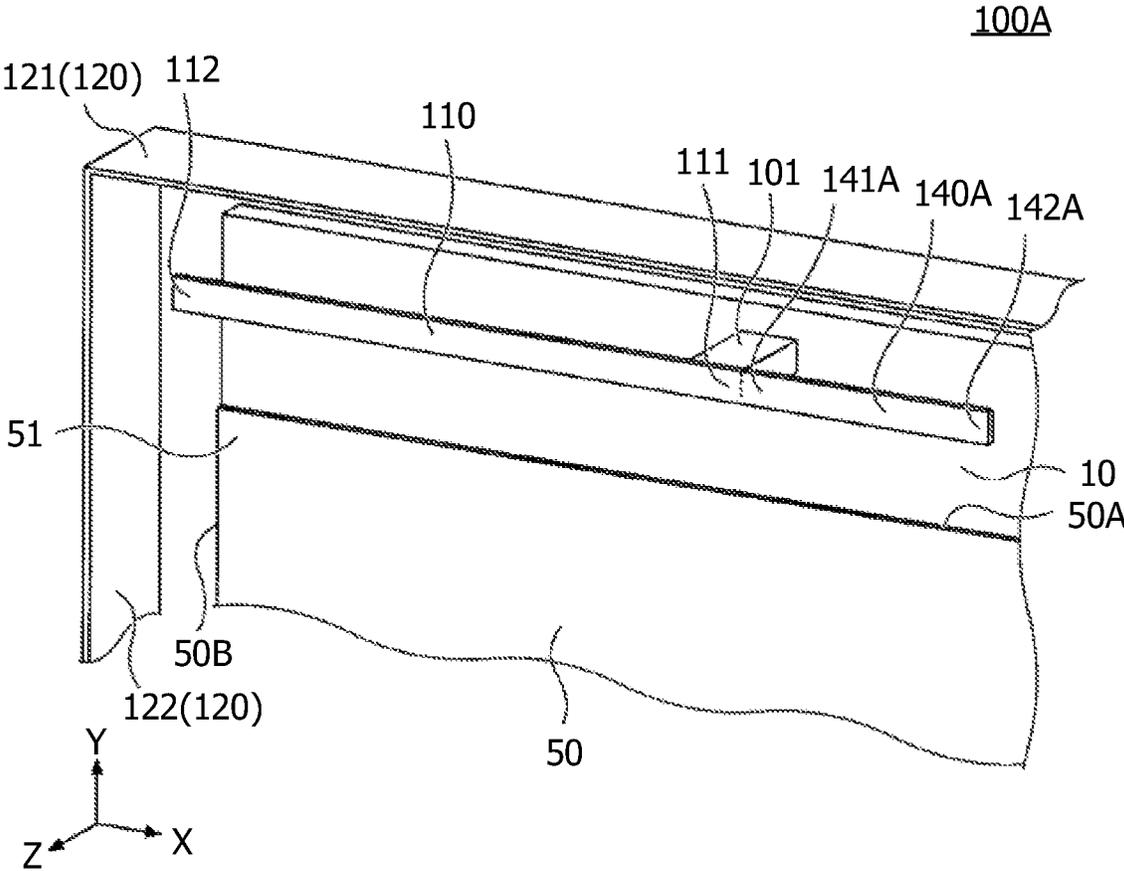


FIG. 20

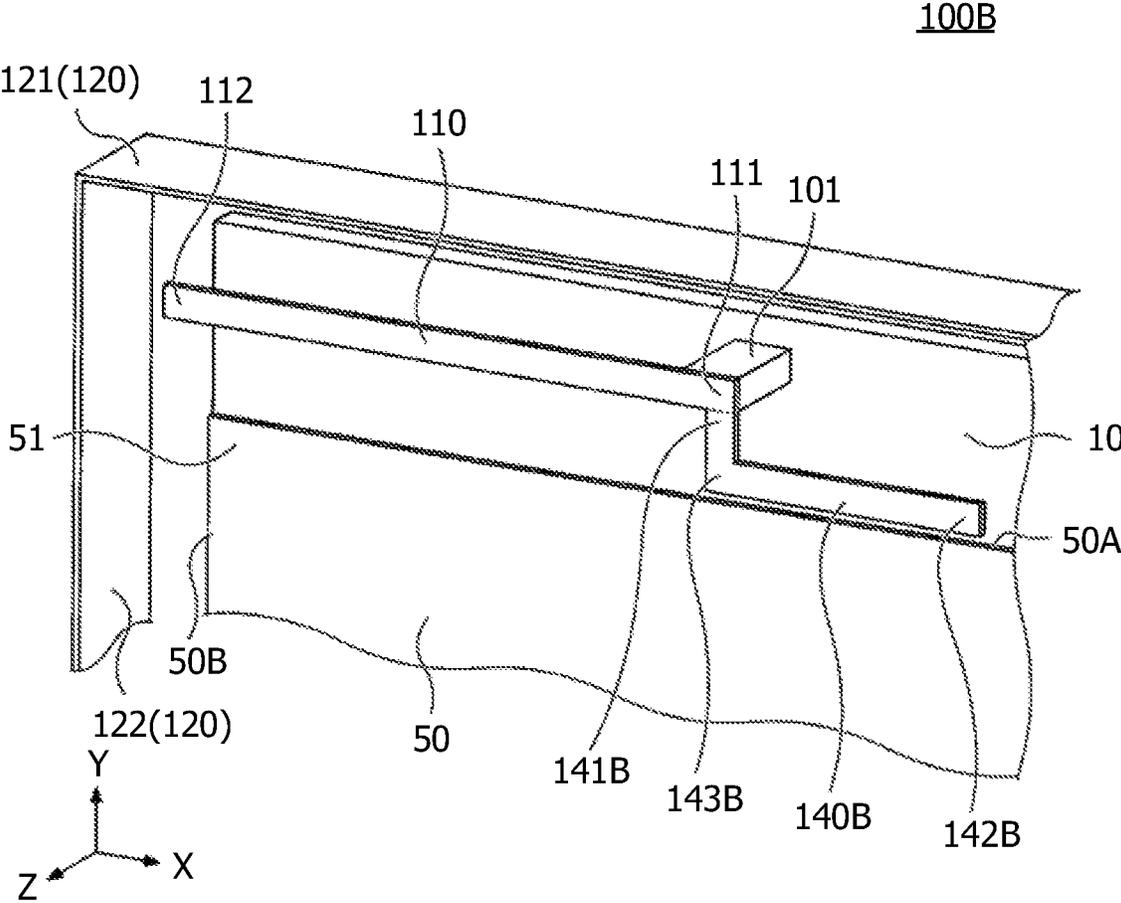


FIG. 21

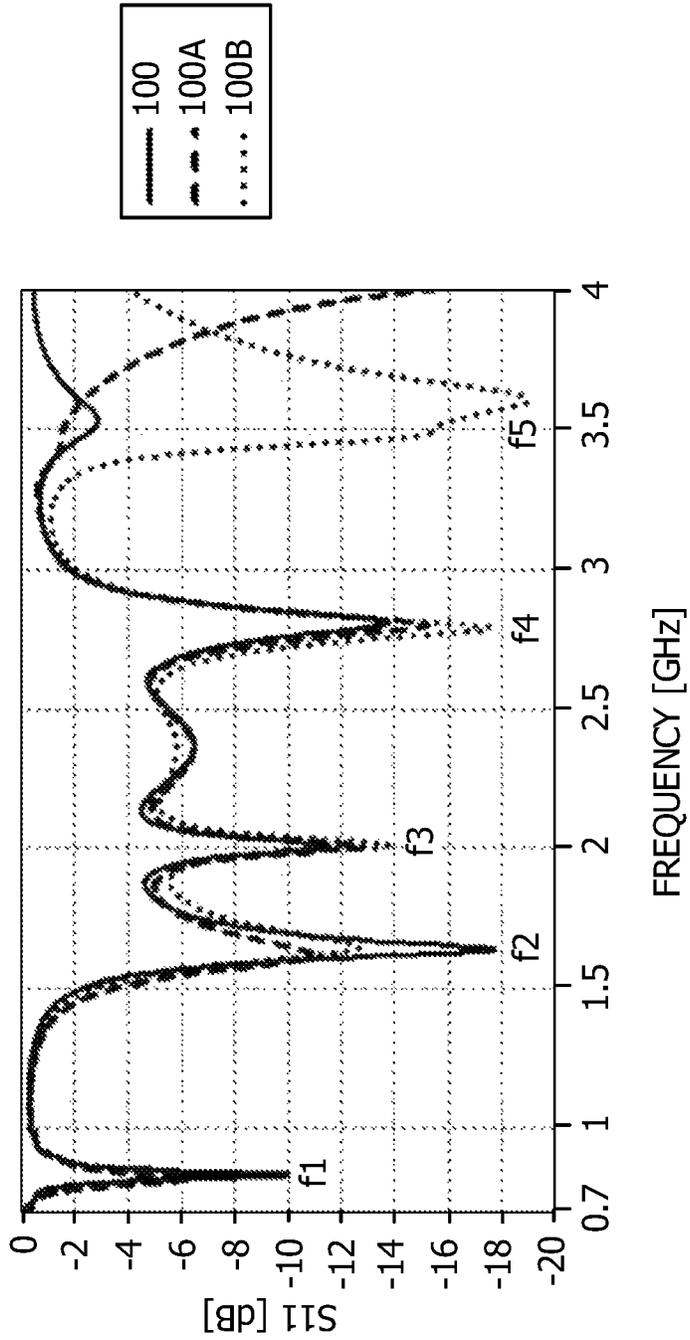


FIG. 22

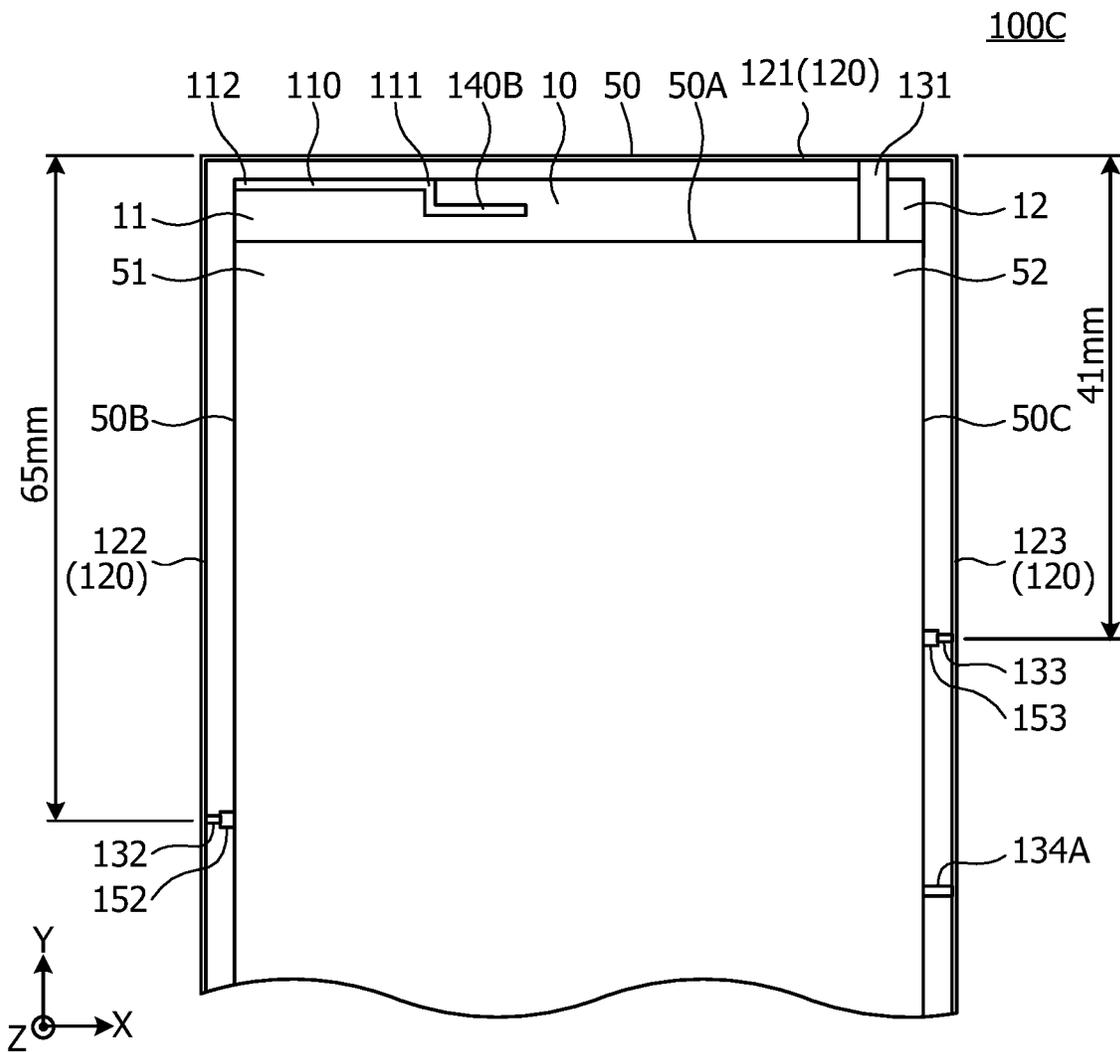


FIG. 23

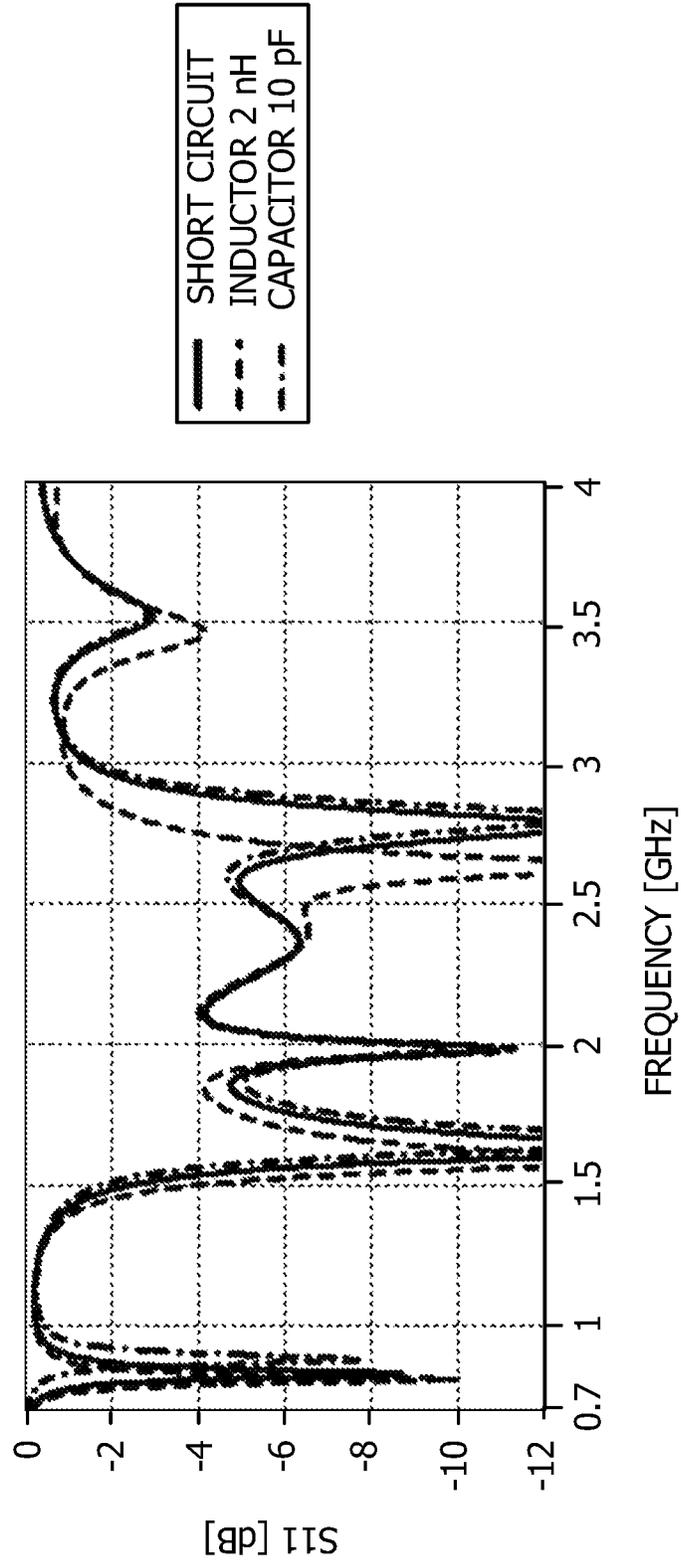
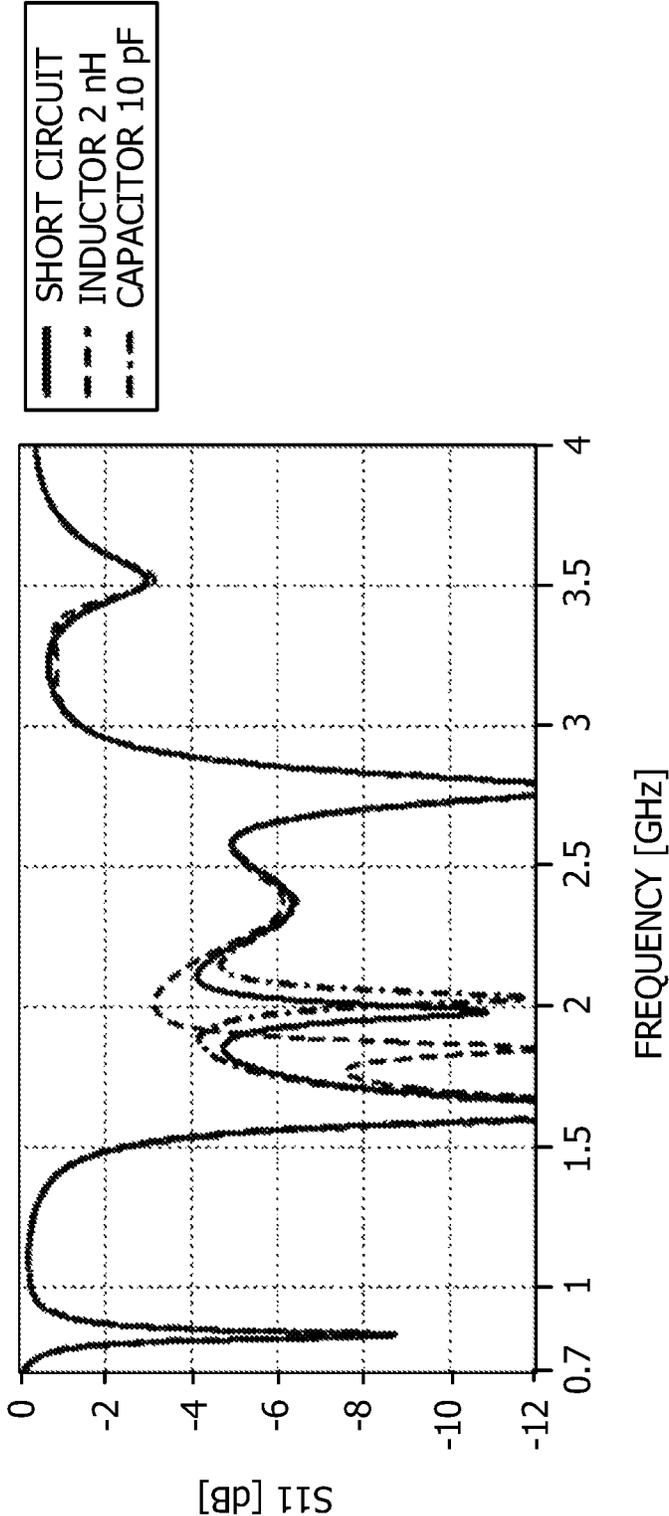


FIG. 24



ANTENNA DEVICE AND WIRELESS COMMUNICATION DEVICE

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation application of International Application PCT/JP2018/012696 filed on Mar. 28, 2018 and designated the U.S., the entire contents of which are incorporated herein by reference. The International Application PCT/JP2018/012696 is based upon and claims the benefit of priority of the prior Japanese Patent Application No. 2017-118088, filed on Jun. 15, 2017, the entire contents of which are incorporated herein by reference.

FIELD

The embodiments discussed herein are related to antenna devices and wireless communication devices.

BACKGROUND

Conventionally, an antenna device is provided.

Related art is disclosed in Japanese Laid-open Patent Publication No. 2010-028521.

SUMMARY

According to one aspect of the embodiments, an antenna device includes: a ground plane which has an edge side; a metal member arranged along the edge side of the ground plane; a first connection line which couples the metal member and the ground plane; a second connection line which couples the metal member and the ground plane; and a power feeding element which has a power feeding point, extends along the metal member from the power feeding point between the first connection line and the second connection line, and is electromagnetic-field-coupled to the metal member.

The object and advantages of the invention will be realized and attained by means of the elements and combinations particularly pointed out in the claims.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory and are not restrictive of the invention.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is a diagram depicting a wireless communication device 200 including an antenna device 100 of an embodiment.

FIG. 2 is a diagram depicting the wireless communication device 200 including the antenna device 100 of the embodiment.

FIG. 3 is a diagram depicting the antenna device 100.

FIG. 4 is a plan view of the antenna device 100 in an enlarged manner.

FIG. 5 is a perspective view of the antenna device 100 in an enlarged manner.

FIG. 6 is a diagram depicting dimensions of each unit of the wireless communication device 200 including the antenna device 100 of the embodiment.

FIG. 7 is a diagram depicting dimensions of each unit of the antenna device 100 of the embodiment.

FIG. 8 is a diagram depicting a frequency characteristic of an S11 parameter of the antenna device 100.

FIG. 9 is a diagram depicting a frequency characteristic of total efficiency of the antenna device 100.

FIG. 10 is a diagram depicting a current distribution of the antenna device 100.

FIG. 11 is a diagram depicting a current distribution of the antenna device 100.

FIG. 12 is a diagram depicting a current distribution of the antenna device 100.

FIG. 13 is a diagram depicting a current distribution of the antenna device 100.

FIG. 14 is a diagram depicting dependency of frequency characteristics of the S11 parameter with respect to the length of a power feeding element 110.

FIG. 15 is a diagram depicting differences in frequency characteristic of the S11 parameter depending on the presence or absence of a housing 210.

FIG. 16 is a diagram depicting frequency characteristics of the S11 parameter when the position of a connection line 132 is changed.

FIG. 17 is a diagram depicting frequency characteristics of the S11 parameter when the position of a connection line 133 is changed.

FIG. 18 is a diagram depicting frequency characteristics of the S11 parameter when the position of a connection line 131 is changed.

FIG. 19 is a diagram depicting an antenna device 100A of a modification example of the embodiment.

FIG. 20 is a diagram depicting an antenna device 100B of a modification example of the embodiment.

FIG. 21 is a diagram depicting frequency characteristics of the S11 parameter of the antenna devices 100, 100A, and 100B.

FIG. 22 is a diagram depicting an antenna device 100C of a modification example of the embodiment.

FIG. 23 is a diagram depicting frequency characteristics of the S11 parameter of the antenna device 100C when the impedance of an adjustment circuit 152 is changed.

FIG. 24 is a diagram depicting frequency characteristics of the S11 parameter of the antenna device 100C when the impedance of an adjustment circuit 153 is changed.

DESCRIPTION OF EMBODIMENTS

For example, an antenna device includes a power feeding element, a parasitic element capable of being coupled to the power feeding element in a high frequency manner, a substrate for generating electric images of the power feeding element and the parasitic element, and switching means which switches, for each of a plurality of switching locations defined in advance of the parasitic element, between a short-circuited state in which the switching location and the substrate are short-circuited and an open state in which the switching location is opened.

Meanwhile, the antenna device achieves a plurality of resonance frequencies by switching the switching means (switch), and the structure may not be simple.

An antenna device with a simple structure and a wireless communication device may be provided.

In the following, an embodiment to which the antenna device and the wireless communication device of the present invention are applied is described.

Embodiment

FIG. 1 and FIG. 2 are diagrams depicting a wireless communication device 200 including an antenna device 100 of an embodiment. FIG. 3 is a diagram depicting the antenna

device **100**. FIG. 4 and FIG. 5 are a plan view and a perspective view of the antenna device **100** in an enlarged manner. In the following, description is made by defining an XYZ coordinate system. Also, a planar view refers to an XY planar view.

The wireless communication device **200** includes a wiring substrate **10**, the antenna device **100**, a housing **210**, a duplexer (DUP) **310**, a low noise amplifier (LNA)/power amplifier (PA) **320**, a modulator/demodulator **330**, and a central processing unit (CPU) chip **340**. The wireless communication device **200** is included in an electronic device such as, for example, a smartphone terminal or a tablet computer.

The antenna device **100** includes a ground plane **50**, a contact spring **101**, a power feeding element **110**, a metal plate **120**, and connection lines **131**, **132**, **133**, **134A**, **134B**, **134C**, **134D**, **135A**, **135B**, **135C**, and **135D**.

The housing **210** depicted in FIG. 1 has a rectangular annular shape in a planar view, and is arranged so as to surround the outer periphery of the wiring substrate **10**. In FIG. 1, the housing **210** is depicted in gray. The housing **210** is made of resin, and a positive direction side (right side) of the X axis and a negative direction side (left side) of the X axis are fixed in a state of being interposed by the ground plane **50** and the metal plate **120**. In FIG. 1, although depiction is omitted, in a state in which an electronic device including the wireless communication device **200** is assembled, a cover is provided on a positive direction side of the Z axis of the ground plane **50**, and is fixed to the housing **210**. Also, when the electronic device including the wireless communication device **200** includes a display panel and/or touch panel, by way of example, the display panel and/or touch panel is arranged on a negative direction side of the Z axis of the wiring substrate **10**.

Since the DUP **310**, the LNA/PA **320**, the modulator/demodulator **330**, and the CPU chip **340** depicted in FIG. 2 are provided on a surface opposite to a surface where the antenna device **100** of the wiring substrate **10** is implemented, the position of the antenna device **100** is indicated by broken lines in FIG. 2.

Here, the DUP **310**, the LNA/PA **320**, the modulator/demodulator **330**, and the CPU chip **340** are described first. The DUP **310**, the LNA/PA **320**, the modulator/demodulator **330**, and the CPU chip **340** are connected via a wiring **360**.

The DUP **310** is connected to the antenna device **100** via a wiring **350** and a via not depicted to perform switching between transmission and reception. Since the DUP **310** has a function as a filter, when the antenna device **100** receives signals of a plurality of frequencies, the signals of the respective frequencies may be separated inside.

The LNA/PA **320** amplifies power of transmission waves and reception waves. The modulator/demodulator **330** performs modulation of transmission waves and demodulation of reception waves. The CPU chip **340** has a function as a communication-purpose processor which performs communication process of the electronic device including the wireless communication device **200** and a function as an application processor which executes an application program. Note that the CPU chip **340** has an internal memory which stores data to be transmitted or data to be received and so forth.

Note that the wirings **350** and **360** are formed by, for example, patterning a copper foil on the surface of the wiring substrate **10**. Also, although omitted in FIG. 2, a matching circuit for adjusting an impedance characteristic is provided between the antenna device **100** and the DUP **310**.

Next, the antenna device **100** is described.

The wiring substrate **10** is, for example, a wiring substrate under flame retardant type 4 (FR-4) standards, and has an insulating layer **10A** and the ground plane **50**. The insulating layer **10A** is, for example, a prepreg layer. The wiring substrate **10** may be configured to have a plurality of insulating layers **10A**. On the outer periphery of the wiring substrate **10**, the housing **210** and the metal plate **120** are provided.

The ground plane **50** is a metal layer arranged on a surface or inner layer of the wiring substrate **10**. Here, by way of example, the ground plane **50** is provided on the back surface of the wiring substrate **10**. The wiring substrate **10** has a rectangular shape in a planar view, and has vertexes **11**, **12**, **13**, and **14**. The ground plane **50** is not provided to an end on the Y axis positive direction side and an end on the Y axis negative direction side of the front surface of the wiring substrate **10** on the Z axis positive direction side, and the insulating layer **10A** of the wiring substrate **10** is exposed.

The ground plane **50** is a metal layer retained at a ground potential, and is a rectangular metal layer having vertexes **51**, **52**, **53**, and **54**. The vertexes **51**, **52**, **53**, and **54** are respectively positioned near the vertexes **11**, **12**, **13**, and **14** of the wiring substrate **10**. The ground plane **50** may be handled as a ground layer, a grounding plate, or a bottom board.

The ground plane **50** has edge sides **50A**, **50B**, **50C**, and **50D**. The edge side **50A** is a side connecting the vertexes **51** and **52**, the edge side **50B** is a side connecting the vertexes **51** and **54**, the edge side **50C** is a side connecting the vertexes **52** and **53**, and the edge side **50D** is a side connecting the vertexes **53** and **54**. The edge sides **50A** and **50D** are positioned to be offset from an edge side of the wiring substrate **10** on the Y axis positive direction side (edge side between the vertexes **11** and **12**) and an edge side thereof on the Y axis negative direction side (edge side between the vertexes **13** and **14**). Thus, the insulating layer **10A** of the wiring substrate **10** is exposed on the Y axis positive direction side and the Y axis negative direction side of the edge sides **50A** and **50D**. Also, the edge sides **50B** and **50C** are at the substantially same positions as those of an edge side of the wiring substrate **10** on the X axis positive direction side (edge side between the vertexes **12** and **13**) and an edge side thereof on the X axis negative direction side (edge side between the vertexes **11** and **14**).

Also, on the edge side **50A** of the ground plane **50**, a point corresponding to a power feeding point **111** of the power feeding element **110** in the X axis direction (hereinafter referred to as a ground point **55**) is a point to which a shield line of a coaxial cable is connected when a core wire of the coaxial cable is connected to the power feeding point of the power feeding element **110**, for example.

Note that while the ground plane **50** with the edge sides **50A**, **50B**, **50C**, and **50D** each being linear is depicted herein, any edge side may not be linear, for example, with asperities provided so as to match the internal shape of the housing of the electronic device including the antenna device **100**, or the like.

The contact spring **101** is arranged on the front surface of the insulating layer **10A** to connect the power feeding point **111** of the power feeding element **110** and the via penetrating through the insulating layer **10A**. The via penetrating through the insulating layer **10A** is connected to the wiring **350**. The spring of the contact spring **101** itself is surrounded by the resin-made housing, and is not viewable from outside.

The power feeding element **110** has the power feeding point **111** and an open end **112**. The power feeding element

110 is a linear power feeding element extending along the line **121** of the metal plate **120** from the power feeding point **111** along the open end **112**. The power feeding element **110** extends to the X axis direction in parallel with the line **121**, and is electromagnetic-field-coupled to the line **121**. The power feeding element **110** is provided to feed power to the metal plate **120**. Note that the power feeding element **110** may be handled as an antenna element.

The metal plate **120** is a metal member in a rectangular annular shape in a planar view having lines **121**, **122**, **123**, and **124**. Each of the lines **121**, **122**, **123**, and **124** is a thin-plate-shaped, narrowly-elongated metal member, with a longitudinal direction being in a direction in which a side surface is viewable in a planar view (X axis direction or Y axis direction).

The lines **121**, **122**, **123**, and **124** are respectively arranged so as to be opposed to the edge side between the vertexes **11** and **12**, the edge side between vertexes **11** and **14**, the edge side between the vertexes **12** and **13**, and the edge side between the vertexes **13** and **14** of the wiring substrate **10**. The lines **121**, **122**, **123**, and **124** are connected in a rectangular annular shape in a clockwise direction in the order of the lines **121**, **123**, **124**, and **122** in a planar view.

The metal plate **120** is arranged so as to surround the outer periphery of the wiring substrate **10**, and has a role in reinforcing the housing **210** and a role in functioning as a radiation element in cooperation with the power feeding element **110**. The metal plate **120** is one example of a metal member.

The line **121** extends to the X axis direction on the Y axis positive direction side of the wiring substrate **10**, and is connected to the edge side **50A** of the ground plane **50** by the connection line **131**. Also, the lines **122** and **123** are connected to both ends of the line **121**.

A location where the connection line **131** is connected to the line **121** is a side near an end of the line **121** on the X axis positive direction side (a point of connection with the line **123**). Also, on a side near an end on the X axis negative direction side (a point of connection with the line **122**), the line **121** is arranged in parallel with the power feeding element **110**.

A space in the Y axis direction between the line **121** and the power feeding element **110** is a space to the extent that electromagnetic field coupling occurs between the power feeding element **110** and the line **121** when power is fed to the power feeding element **110**. The line **121** is fed with power by the power feeding element **110**. Note that feeding the line **121** with power by the power feeding element **110** is synonymous with feeding at least part of the metal plate **120** with power by the power feeding element **110**.

The line **122** extends to the Y axis direction on the X axis negative direction side of the wiring substrate **10**, and is connected to the edge side **50B** of the ground plane **50** by the connection lines **132**, **135A**, **135B**, **135C**, and **135D**. Also, the lines **121** and **124** are connected to both ends of the line **122**.

The positions of the connection lines **132**, **135A**, **135B**, **135C**, and **135D** are defined based on a relation between the line **121** and the connection line **131** and a relation between the line **123** and the connection line **133**. Details about the positions of the connection lines **132**, **135A**, **135B**, **135C**, and **135D** will be described further below.

The line **123** extends to the Y axis direction on the X axis positive direction side of the wiring substrate **10**, and is connected to the edge side **50C** of the ground plane **50** by the

connection lines **133**, **134A**, **134B**, **134C**, and **134D**. Also, the lines **121** and **124** are connected to both ends of the line **123**.

The positions of the connection lines **133**, **134A**, **134B**, **134C**, and **134D** are defined based on a relation between the line **121** and the connection line **131** and a relation between the line **122** and the connection line **132**. Details about the positions of the connection lines **133**, **134A**, **134B**, **134C**, and **134D** will be described further below.

The line **124** extends to the X axis direction on the Y axis negative direction side of the wiring substrate **10**, and has the wirings **122** and **123** connected to both ends. The line **124** is retained by the lines **122** and **123**, and has not connected thereto connection lines such as the connection lines **131**, **132**, and **133**.

The connection line **131** extends from the edge side **50A** to the Y axis positive direction on a side near the vertex **52** (X axis positive direction side) rather than the vertex **51** of the ground plane **50**, and is connected to the line **121**. The connection line **131** is one example of a first connection line.

When power is fed to the power feeding element **110**, a loop current flows through the connection line **131**, the line **121**, the power feeding element **110**, and the edge side **50A** (a portion between the ground point **55** and a connection point between the ground plane **50** and the connection line **131**). This is because the power feeding element **110** and mainly the lines **121** and **122** of the metal plate **120** are electromagnetic-field-coupled, the power feeding point **111** is connected to the core wire of the coaxial cable, and the ground point **55** is connected to the shield line of the coaxial cable, thereby causing a loop to occur in an alternating manner.

Thus, the distance between the ground point **55** and the connection point between the ground plane **50** and the connection line **131** is set at a distance represented by a length of $\frac{1}{2}$ of the electrical length of the wavelength at a frequency **f4**. Here, as described above, the edge side **50A** of the ground plane **50** may not be linear. Also in this case, it is only required that the distance between the ground point **55** and the connection point between the ground plane **50** and the connection line **131** is set at a distance represented by a length $(\frac{4}{2})$, which is $\frac{1}{2}$ of the electrical length of a wavelength **4** at the frequency **f4**. Note that the frequency **f4** is, by way of example, 2.4 GHz, and is a frequency higher than frequencies **f1**, **f2**, and **f3**, which will be described further below.

The length $(\frac{4}{2})$, which is $\frac{1}{2}$ of the electrical length of the wavelength **4** at the frequency **f4**, is one example of a length corresponding to a length of $\frac{1}{2}$ of the wavelength **4** at the frequency **f4**.

The connection line **132** constructs a loop antenna in cooperation with the connection line **131**, the lines **121** and **122** of the metal plate **120**, the edge side **50A**, and the edge side **50B**. The connection line **132** is one example of a second connection line.

Here, the length of the loop constructed of the connection lines **131** and **132**, the lines **121** and **122** of the metal plate **120**, the edge side **50A**, and the edge side **50B** is an electrical length (1) of a wavelength at the frequency **f1**, and is also a length which is a double of the electrical length (2) of a wavelength at the frequency **f2** which is double of the frequency **f1**. This loop is one example of a first loop.

To construct a loop antenna which resonates at the frequency **f1**, the length of the metal plate **120** between the connection line **131** and the connection line **132** is set at a length $(\frac{1}{2})$, which is $\frac{1}{2}$ of the electrical length of the wavelength **1** at the frequency **f1**. The frequency **f1** is, by

way of example, 0.85 GHz, which is a frequency lower than the frequencies **f2**, **f3**, and **f4**.

The length ($\frac{1}{2}$), which is $\frac{1}{2}$ of the electrical length (1) of the wavelength at the frequency **f1**, is one example of a length corresponding to $\frac{1}{2}$ of a first wavelength at the frequency **f1**.

Note that the length of the metal plate **120** between the connection line **131** and the connection line **132** is a length between a connection point where the metal plate **120** (line **121**) is connected to the connection line **131** and a connection point where the metal plate **120** (line **122**) is connected to the connection line **132**, but may include at least part of the length of the connection line **131** and/or the connection line **132**.

To construct a loop antenna which resonates at the frequency **f2**, the length of the metal plate **120** between the connection line **131** and the connection line **132** is set at an electrical length (2) of the wavelength **2** at a frequency **f2**. The frequency **f2** is, by way of example, 1.65 GHz, which is a frequency lower than the frequencies **f3** and **f4**.

The electrical length (2) of the wavelength at the frequency **f2** is one example of a length corresponding to a second wavelength at a second frequency.

The connection line **133** constructs a loop antenna in cooperation with the connection line **131**, the lines **121** and **123** of the metal plate **120**, the edge side **50A**, and the edge side **50C**. The connection line **133** is one example of a third connection line.

This is because when power is fed to the power feeding element **110**, a current flows through the line **121** of the metal plate **120** and the connection line **131**, and thus flows also through the loop including the connection lines **131** and **133**. This loop is one example of a second loop.

Here, the length of the loop constructed of the connection lines **131** and **133**, the lines **121** and **123** of the metal plate **120**, the edge side **50A**, and the edge side **50C** is an electrical length (3) of a wavelength at the frequency **f3**.

To construct a loop antenna which resonates at the frequency **f3**, the length of the metal plate **120** between the connection line **131** and the connection line **133** is set at a length ($\frac{3}{2}$), which is $\frac{1}{2}$ of the electrical length of the wavelength **3** at the frequency **f3**. The frequency **f3** is, by way of example, 2.0 GHz.

Also, the length ($\frac{3}{2}$), which is $\frac{1}{2}$ of the electrical length of the wavelength **3** at the frequency **f3**, is one example of a length corresponding to $\frac{1}{2}$ of a third wavelength at a third frequency.

Note that the length of the metal plate **120** between the connection line **131** and the connection line **133** is a length between a connection point where the metal plate **120** (line **121**) is connected to the connection line **131** and a connection point where the metal plate **120** (line **123**) is connected to the connection line **133**, but may be thought to include at least part of the length of the connection line **131** and/or the connection line **133**.

The connection lines **134A**, **134B**, **134C**, and **134D** are provided on the Y axis negative direction side of the connection line **133** in this order so as to connect between the edge side **50C** of the ground plane **50** and the line **123** of the metal plate **120**.

The position of the connection line **134A** is set so that the length of a loop constructed of the connection line **133**, the connection line **134A**, the line **123** of the metal plate **120**, and the edge side **50C** is shorter than the electrical length (3) of the wavelength **4** at the highest frequency **f4** among the frequencies **f1**, **f2**, **f3**, and **f4**.

In other words, the length between the connection line **134A** and the connection line **133** of the metal plate **120** is set so as to be shorter than the length ($\frac{4}{2}$), which is $\frac{1}{2}$ of the electrical length of the wavelength **4** at the frequency **f4**.

This is to restrain resonance adjacent to the frequencies **f1**, **f2**, **f3**, and **f4** from occurring in the loop constructed of the connection line **133**, the connection line **134A**, the line **123** of the metal plate **120**, and the edge side **50C**. For example, when resonance adjacent to a band at the frequency **f4** occurs, the characteristic at the frequency **f4** itself may be degraded. The same goes for the frequencies **f1**, **f2**, and **f3**.

Note that it is only required that the positions of the connection lines **134B**, **134C**, and **134D** are set so that the length of the metal plate **120** between each of these connection lines **134B**, **134C**, and **134D** and its relevant one of the connection lines **134A**, **134B**, and **134C** adjacent on the Y axis positive direction side is shorter than the length ($\frac{4}{2}$), which is $\frac{1}{2}$ of the electrical length of the wavelength **4** at the frequency **f4**. However, as compared with the connection line **134A**, the connection lines **134B**, **134C**, and **134D** are positioned further away from the connection line **133**. Therefore, the positional constraint as described above may not be provided if there is no possibility of occurrence of characteristic degradation due to occurrence of resonance.

The connection lines **135A**, **135B**, **135C**, and **135D** are provided on the Y axis negative direction side of the connection line **132** in this order so as to connect between the edge side **50B** of the ground plane **50** and the line **122** of the metal plate **120**.

The position of the connection line **135A** is set so that the length of a loop constructed of the connection line **132**, the connection line **135A**, the line **122** of the metal plate **120**, and the edge side **50B** is shorter than the electrical length (3) of the wavelength **4** at the highest frequency **f4** among the frequencies **f1**, **f2**, **f3**, and **f4**.

In other words, the length between the connection line **135A** and the connection line **132** of the metal plate **120** is set so as to be shorter than the length ($\frac{4}{2}$), which is $\frac{1}{2}$ of the electrical length of the wavelength **4** at the frequency **f4**. The reason for this is similar to the reason for setting the position of the connection line **134A** with respect to the connection line **133**. The positions of the connection lines **135B**, **135C**, and **135D** is also set in a similar manner as for the positions of the connection lines **134B**, **134C**, and **134D**.

FIG. 6 and FIG. 7 are diagrams depicting dimensions of each unit of the wireless communication device **200** including the antenna device **100** of the embodiment.

As depicted in FIG. 6, the length of the metal plate **120** in the X axis direction (the length of each of the lines **121** and **124**) is 74 mm. The length of the metal plate **120** in the Y axis direction (the length of each of the lines **122** and **123**) is 156 mm. Also, the width of the metal plate **120** in the Z axis direction is 4.5 mm.

As depicted in FIG. 7, the length of the power feeding element **110** in the X axis direction is 20 mm. The length of the connection line **131** in the Y axis direction is 9 mm. The length of the line **121** on the X axis positive direction side of the connection line **131** is 7 mm.

The length of the metal plate **120** between a joint part between the lines **121** and **123** and the connection line **133** is 46 mm. The length of the metal plate **120** between the connection lines **133** and **134A** is 24 mm. The length of the metal plate **120** between the connection lines **134A** and **134B**, the length thereof between the connection lines **134B** and **134C**, and the length thereof between the connection lines **134C** and **134D** are 24 mm each.

The length of the metal plate **120** between a joint part between the lines **121** and **122** and the connection line **132** is 65 mm. The length of the metal plate **120** between the connection lines **132** and **135A**, the length thereof between the connection lines **135A** and **135B**, the length thereof between the connection lines **135B** and **135C**, and the length thereof between the connection lines **135C** and **135D** are 20 mm each. Also, the width of the ground plane **50** in the X axis direction is 68 mm.

FIG. **8** is a diagram depicting a frequency characteristic of an **S11** parameter of the antenna device **100**. FIG. **9** is a diagram depicting a frequency characteristic of total efficiency of the antenna device **100**. FIG. **8** and FIG. **9** depict results acquired from electromagnetic field simulations.

As depicted in FIG. **8**, in the frequency characteristic of the **S11** parameter, it was found that the **S11** parameter is equal to or lower than -6 dB at frequencies **f1** (0.85 GHz), **f2** (1.65 GHz), **f3** (2.0 GHz), and **f4** (2.4 GHz), allowing a favorable radiation characteristic with less radiation to be acquired.

Also as depicted in FIG. **9**, in the frequency characteristic of total efficiency, it was found that total efficiency is equal to or higher than -3 dB at the frequencies **f1** (0.85 GHz), **f2** (1.65 GHz), **f3** (2.0 GHz), and **f4** (2.4 GHz), allowing a favorable radiation characteristic to be acquired.

FIG. **10** to FIG. **13** are diagrams each depicting a current distribution of the antenna device **100**. The current distributions of FIG. **10** to FIG. **13** have been acquired from electromagnetic field simulations, and each depict a current distribution at the frequencies **f1** (0.85 GHz), **f2** (1.65 GHz), **f3** (2.0 GHz), and **f4** (2.4 GHz). Note that each current distribution represents that the current density is higher as the current distribution is blacker (thicker) and the current density is lower as the current distribution is whiter (thinner).

At the frequency **f1** (0.85 GHz) depicted in FIG. **10**, it is found that a current flows through the power feeding element **110** and flows through a loop constructed of the connection line **131**, the line **121**, the line **122**, the connection line **132**, the edge side **50B**, and the edge side **50A**. In particular, since current density of the connection lines **131** and **132** is high, it is found that antinodes of resonance current occur at two locations, that is, the connection lines **131** and **132**. Also, since current density of a connection part between the lines **121** and **122** and the vertex **51** is low, it is found that nodes of resonance current occur at two locations, that is, the connection part between the lines **121** and **122** and the vertex **51**.

That is, from the current distribution depicted in FIG. **10**, it is found that resonance for one wavelength occurs in the loop constructed of the connection line **131**, the line **121**, the line **122**, the connection line **132**, the edge side **50B**, and the edge side **50A**. In other words, it is found that a portion having the length ($1/2$), which is $1/2$ of the electrical length of the wavelength **1** at the frequency **f1**, extends between the connection line **131** and the connection line **132** of the metal plate **120**.

At the frequency **f2** (1.65 GHz) depicted in FIG. **11**, it is found that a current flows through the power feeding element **110** and flows through the loop constructed of the connection line **131**, the line **121**, the line **122**, the connection line **132**, the edge side **50B**, and the edge side **50A**. In particular, since current density of the connection lines **131** and **132**, the connection part between the lines **121** and **122**, and the vertex **51** is high, it is found that antinodes of resonance current occur at four locations, that is, the connection lines **131** and **132**, the connection part between the

lines **121** and **122**, and the vertex **51**, and also current density is low and nodes of resonance current occur at four locations between these.

That is, from the current distribution depicted in FIG. **11**, it is found that resonance for two wavelengths occurs in the loop constructed of the connection line **131**, the line **121**, the line **122**, the connection line **132**, the edge side **50B**, and the edge side **50A**. In other words, it is found that a portion having the electrical length (2) of the wavelength **2** at the frequency **f2** extends between the connection line **131** and the connection line **132** of the metal plate **120**.

From FIG. **10** and FIG. **11**, it was confirmed that resonance for one wavelength and resonance for two wavelengths occur in the loop constructed of the connection line **131**, the line **121**, the line **122**, the connection line **132**, the edge side **50B**, and the edge side **50A** and resonance at the frequency **f1** (0.85 GHz) and the frequency **f2** (1.65 GHz), which is approximately double the frequency **f1**, occurs.

At the frequency **f3** (2.0 GHz) depicted in FIG. **12**, it is found that a current flows through the power feeding element **110** and flows through a loop constructed of the connection line **131**, the line **121**, the line **123**, the connection line **133**, the edge side **50C**, and the edge side **50A**. In particular, since current density of the connection lines **131** and **133** is high, it is found that antinodes of resonance current occur at two locations, that is, the connection lines **131** and **133**. Also, since current density of a portion between the antinodes at the two locations is low, it is found that two antinodes and two nodes of resonance current occur.

That is, from the current distribution depicted in FIG. **12**, it is found that resonance for one wavelength occurs in the loop constructed of the connection line **131**, the line **121**, the line **123**, the connection line **133**, the edge side **50C**, and the edge side **50A**. In other words, it is found that a portion having the length ($3/2$), which is $1/2$ of the electrical length of the wavelength **3** at the frequency **f3**, extends between the connection line **131** and the connection line **132** of the metal plate **120**.

At the frequency **f4** (2.4 GHz) depicted in FIG. **13**, it is found that a current flows through the power feeding element **110** and a loop current flows through the line **121**, the connection line **131**, the edge side **50A**, and the power feeding element **110**. In particular, since current density of the power feeding element **110** and the connection line **131** is high, it is found that antinodes of resonance current occur at two locations, that is, the power feeding element **110** and the connection line **131**. Also, since current density of a portion between the antinodes at the two locations is low, it is found that two antinodes and two nodes of resonance current occur.

That is, from the current distribution depicted in FIG. **13**, it is found that resonance for one wavelength occurs in the loop-shaped portion constructed of the line **121**, the connection line **131**, the edge side **50A**, and the power feeding element **110**. In other words, it is found that a portion having the length ($4/2$), which is $1/2$ of the electrical length of the wavelength **4** at the frequency **f4**, extends in a portion of the edge side **50A** between the power feeding element **110** and the connection line **131**.

FIG. **14** is a diagram depicting dependency of frequency characteristics of the **S11** parameter with respect to the length of the power feeding element **110**. Here, in a simulation, frequency characteristics of the **S11** parameter are described when the length of the power feeding element **110** is set at 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm by

changing the position of the power feeding point **111**, with the position of the open end **112** of the power feeding element **110** being fixed.

When the length of the power feeding element **110** is 15 mm, 20 mm, and 25 mm, substantially favorable values were acquired at the frequencies **f1** (0.85 GHz), **f2** (1.65 GHz), **f3** (2.0 GHz), and **f4** (2.4 GHz). However, when the length of the power feeding element **110** is 10 mm and 30 mm, a tendency of reflection to increase was observed.

In particular, when comparisons at the frequency **f2** (1.65 GHz) are made among the cases when the length of the power feeding element **110** is 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm, fluctuations of the **S11** parameter were significant. When the length of the power feeding element **110** is 10 mm and 30 mm, the **S11** parameter significantly exceeded -6 dB, and a favorable radiation characteristic was not acquired. From this, it was found that the length of the power feeding element **110** is preferably set within a range longer than 10 mm and shorter than 30 mm.

Here, since the metal plate **120** is positioned near the housing **210**, a wavelength shortening effect occurs. When a wavelength shortening ratio is set at 0.7 to find a wavelength (electrical length 2) at 1.65 GHz, 2 is approximately 131 mm. A range longer than 10 mm and shorter than 30 mm may be represented as $0.07 < \frac{2}{\text{length of the power feeding element } 110} < 0.2$ when normalized by the wavelength at 1.65 GHz.

FIG. **15** is a diagram depicting differences in frequency characteristic of the **S11** parameter depending on the presence or absence of the housing **210**. A characteristic with the housing **210** is indicated by a solid line, and a characteristic without the housing **210** is indicated by a broken line. Here, as compared with the case without the housing **210**, it was confirmed that the **S11** parameter in the case with the housing **210** is shifted to a low frequency side as a whole. From this, it was confirmed that a wavelength shortening effect occurs in the case with the housing **210**.

The frequencies **f1** (0.85 GHz), **f2** (1.65 GHz), **f3** (2.0 GHz), and **f4** (2.4 GHz) in the case with the housing **210** are lower by approximately 30%, as compared with the four frequencies (approximately 1.2 GHz, approximately 2.2 GHz, approximately 2.7 GHz, and approximately 3.0 GHz) in the case without the housing **210**. This represents that the wavelength shortening effect is approximately 30%, which is the result substantially consistent with the wavelength shortening ratio (0.7) described by using FIG. **14**.

FIG. **16** is a diagram depicting frequency characteristics of the **S11** parameter when the position of the connection line **132** is changed. Changing the position of the connection line **132** refers to changing the distance from an end of the line **122** in the Y axis positive direction (a connection part between the lines **121** and **122**) to the connection line **132**. While a mode of 65 mm is depicted in FIG. **7**, frequency characteristics of the **S11** parameter in the case of 60 mm and 55 mm in addition to 65 mm were found herein. Note that the characteristic in the case of 65 mm is indicated by a solid line, the characteristic in the case of 60 mm is indicated by a broken line, and the characteristic in the case of 55 mm is indicated by a one-dot-chain line.

Since the connection line **132** is related to the frequencies **f1** (0.85 GHz) and **f2** (1.65 GHz), the frequencies **f1** (0.85 GHz) and **f2** (1.65 GHz) fluctuated as depicted in FIG. **16**. Specifically, when the position of the connection line **132** was made closer to the end of the line **122** in the Y axis positive direction as 65 mm, 60 mm, and 55 mm, the frequencies **f1** (0.85 GHz) and **f2** (1.65 GHz) were shifted to a high frequency side.

The reason for this occurrence is thought as follows. When the position of the connection line **132** is made closer to the end of the line **122** in the Y axis positive direction, the length of a loop constructed of the connection lines **131** and **132**, the lines **121** and **122** of the metal plate **120**, the edge side **50A**, and the edge side **50B** is shortened and the resonance frequency of the loop antenna is shifted to the high frequency side.

FIG. **17** is a diagram depicting frequency characteristics of the **S11** parameter when the position of the connection line **133** is changed. Changing the position of the connection line **133** refers to changing the distance from an end of the line **123** in the Y axis positive direction (a connection part between the lines **121** and **123**) to the connection line **133**. While a mode of 46 mm is depicted in FIG. **7**, frequency characteristics of the **S11** parameter in the case of 44 mm and 42 mm in addition to 46 mm were found herein. Note that the characteristic in the case of 46 mm is indicated by a solid line, the characteristic in the case of 44 mm is indicated by a broken line, and the characteristic in the case of 42 mm is indicated by a one-dot-chain line.

Since the connection line **133** is related to the frequency **f3** (2.0 GHz), the frequency **f3** (2.0 GHz) fluctuated as depicted in FIG. **17**. Specifically, when the position of the connection line **133** was made closer to the end of the line **123** in the Y axis positive direction as 46 mm, 44 mm, and 42 mm, the frequency **f3** (2.0 GHz) was shifted to a high frequency side.

The reason for this occurrence is thought as follows. When the position of the connection line **133** is made closer to the end of the line **123** in the Y axis positive direction, the length of the loop constructed of the connection lines **131** and **133**, the lines **121** and **123** of the metal plate **120**, the edge side **50A**, and the edge side **50C** is shortened and the resonance frequency of the loop antenna is shifted to the high frequency side.

FIG. **18** is a diagram depicting frequency characteristics of the **S11** parameter when the position of the connection line **131** is changed. Changing the position of the connection line **131** refers to changing the distance from an end of the line **121** in the X axis positive direction (a connection part between the lines **121** and **123**) to the connection line **131**. While a mode of 7 mm is depicted in FIG. **7**, frequency characteristics of the **S11** parameter in the case of 10 mm and 13 mm in addition to 7 mm are depicted herein. Note that the characteristic in the case of 7 mm is indicated by a solid line, the characteristic in the case of 10 mm is indicated by a broken line, and the characteristic in the case of 13 mm is indicated by a one-dot-chain line.

Since the connection line **131** is related to all of the frequencies **f1** (0.85 GHz), **f2** (1.65 GHz), **f3** (2.0 GHz), and **f4** (2.4 GHz), the frequencies **f1** (0.85 GHz), **f2** (1.65 GHz), **f3** (2.0 GHz), and **f4** (2.4 GHz) fluctuated as depicted in FIG. **18**. Specifically, when the position of the connection line **131** was made closer to the end of the line **121** in the X axis positive direction as 13 mm, 10 mm, and 7 mm, the frequencies **f1** (0.85 GHz), **f2** (1.65 GHz), and **f4** (2.4 GHz) were shifted to a low frequency side, and the frequency **f3** (2.0 GHz) was shifted to a high frequency side.

The reason for this is thought as follows. When the position of the connection line **131** is made closer to the end of the line **121** in the X axis positive direction, the loop resonating at the frequencies **f1** (0.85 GHz), **f2** (1.65 GHz), and **f4** (2.4 GHz) becomes long and the resonance frequency is thus shifted to the low frequency side and the loop

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resonating at the frequency **f3** (2.0 GHz) becomes short and the resonance frequency is thus shifted to the high frequency side.

These results are consistent with the fact that a loop current is acquired at the above-described four frequencies **f1** (0.85 GHz), **f2** (1.65 GHz), **f3** (2.0 GHz), and **f4** (2.4 GHz).

As described above, according to the embodiment, the antenna device **100** is acquired, the antenna device **100** being capable of communication at the four frequencies **f1** (0.85 GHz), **f2** (1.65 GHz), **f3** (2.0 GHz), and **f4** (2.4 GHz) with a simple structure using the ground plane **50**, the power feeding element **110**, the metal plate **120**, and the connection lines **131**, **132**, and **133**.

The antenna device **100** is capable of communication at the four bands with a fixed, simple structure including the power feeding element **110**, the metal plate **120**, and the connection lines **131**, **132**, and **133**, without switching connection by a switch or the like. That is, the antenna device **100** rendered multiband with a simple structure may be provided.

Also, since communication at the four bands is not achieved by switching by a switch or the like but is available at any time, it is possible to easily support carrier aggregation.

Also, the metal plate **120** is present on an exterior surface of the wireless communication device **200** including the antenna device **100** and the electronic device, and has a role in reinforcing the housing **210**. This means that the reinforcing member (metal plate **120**) is used as an antenna element. That is, with a simple structure using the reinforcing member as an antenna element, the multiband antenna device **100** capable of supporting carrier aggregation may be provided.

Also, the length of the metal plate **120** between the connection line **134A** and the connection line **133** is set to be shorter than the length (4/2), which is $\frac{1}{2}$ of the electrical length of the wavelength **4** at the frequency **f4**, thereby keeping communication characteristics at the frequencies **f1**, **f2**, **f3**, and **f4** from degradation. The same goes for the position of the connection line **135A**. Since the connection lines **134A** and **135A** are metal members supporting the metal plate **120**, the antenna device **100** rendered multiband with a simple structure is achieved by optimizing the position of the metal members supporting the metal plate **120**.

Note that the mode has been described above in which the four corners (joint parts of the lines **121** to **124**) of the metal plate **120** are each bent at the right angle, but a shape with rounded four corners may be adopted.

Also, a structure may be adopted in which a fifth communication band may be provided by loading a branch element to the power feeding element **110**. FIG. **19** is a diagram depicting an antenna device **100A** of a modification example of the embodiment. FIG. **20** is a diagram depicting an antenna device **100B** of a modification example of the embodiment.

The antenna device **100A** depicted in FIG. **19** has a structure with the power feeding element **110** of the antenna device **100** depicted in FIG. **1** to FIG. **5** additionally provided with a branch element **140A**. The branch element **140A** is a linear antenna element having a connection end **141A** and an open end **142A**.

The branch element **140A** has the connection end **141A** connected to the power feeding point **111**, and extends to the open end **142A** to the X axis direction. The length of the branch element **140A** from the connection end **141A** to the

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open end **142A** is set at a length (5/4), which is $\frac{1}{4}$ of the electrical length of a wavelength **5** at a frequency **f5**.

The frequency **f5** is, by way of example, 3.5 GHz, which is a frequency higher than the frequencies **f1**, **f2**, **f3**, and **f4**. The branch element **140A** functions as a monopole antenna in cooperation with the ground plane **50**, allowing communication at the frequency **f5**. Note that the length of the branch element **140A** is, by way of example, 8.5 mm.

Also, the antenna device **100B** depicted in FIG. **20** has a structure in which a branch element **140B** is added to the power feeding element **110** of the antenna device **100** depicted in FIG. **1** to FIG. **5**. The branch element **140B** is an L-shaped antenna element having a connection end **141B**, an open end **142B**, and a bent part **143B**.

The branch element **140B** has the connection end **141B** connected to the power feeding point **111**, extends from the connection end **141B** to the bent part **143B** to a Y axis negative direction side, is bent at the bent part **143B** at the right angle to the X axis positive direction, and extends to the open end **142B** to the X axis direction.

The length of the branch element **140B** from the connection end **141B** via the bent part **143B** to the open end **142B** is set at a length (5/4), which is $\frac{1}{4}$ of the electrical length of the wavelength **5** at the frequency **f5**. The frequency **f5** is, by way of example, 3.5 GHz. The branch element **140B** functions as a monopole antenna in cooperation with the ground plane **50**, allowing communication at the frequency **f5**. Note that the length of the branch element **140B** is, by way of example, 4 mm between the connection end **141B** and the bent part **143B** and 10 mm between the bent part **143B** and the open end **142B**.

FIG. **21** is a diagram depicting frequency characteristics of the S11 parameter of the antenna devices **100**, **100A**, and **100B**. The characteristic of the antenna device **100** is indicated by a solid line, the characteristic of the antenna device **100A** is indicated by a broken line, and the characteristic of the antenna device **100B** is indicated by a one-dot-chain line. The characteristic of the antenna device **100** is identical to the characteristic depicted in FIG. **8**.

As compared with the antenna device **100**, in the antenna devices **100A** and **100B**, resonance at frequencies higher than the frequency **f4** was acquired. Resonance occurred at approximately 4 GHz in the antenna device **100A**, and resonance occurred at 3.5 GHz (**f5**) in the antenna device **100B**. While the resonance frequency of the antenna device **100A** is higher than **f5**, it is thought that this is adjustable to 3.5 GHz (**f5**) by using a matching circuit.

As depicted in FIG. **19** to FIG. **21**, the antenna device **100A** including the branch element **140A** and the antenna device **100B** including the branch element **140B** are capable of communication at the five bands with a fixed, simple structure. That is, the antenna devices **100A** and **100B** each rendered multiband with a simple structure may be provided.

FIG. **22** is a diagram depicting an antenna device **100C** of a modification example of the embodiment. The antenna device **100C** has a structure in which the branch element **140B** (refer to FIG. **20**) is added to the antenna device **100** depicted in FIG. **4** and adjustment circuits **152** and **153** are inserted between the connection lines **132** and **133** and the ground plane **50**. Note that the length between the connection line **132** and an end of the line **122** on the Y axis positive direction side is 65 mm, and the length between the connection line **133** and an end of the line **123** on the Y axis positive direction side is 41 mm.

FIG. **23** is a diagram depicting frequency characteristics of the S11 parameter of the antenna device **100C** when the

impedance of the adjustment circuit **152** is changed. **S11** parameters were found in the cases in which the adjustment circuit **152** was short-circuited (solid line), an inductor of 2 nH was inserted in series to the connection line **132** (broken line), and a capacitor of 10 pF was inserted in series to the connection line **132** (one-dot-chain line). Note that the case in which the adjustment circuit **152** was short-circuited is the case in which the ground plane **50** and the metal plate **120** were connected by the connection line **132** as depicted in FIG. **4** without insertion of the adjustment circuit **152**.

As compared with the case in which the adjustment circuit **152** was short-circuited, the 800 MHz band and the 1.5 GHz band were shifted to a low frequency side when the inductor was inserted, and the 800 MHz band and the 1.5 GHz band were shifted to a high frequency side when the capacitor was inserted. From this, it was confirmed that the resonance frequency is adjustable by inserting the adjustment circuit **152** as an inductor or capacitor into the connection line **132**.

FIG. **24** is a diagram depicting frequency characteristics of the **S11** parameter of the antenna device **100C** when the impedance of the adjustment circuit **153** is changed. **S11** parameters were found in the cases in which the adjustment circuit **153** was short-circuited (solid line), an inductor of 2 nH was inserted in series to the connection line **133** (broken line), and a capacitor of 10 pF was inserted in series to the connection line **133** (one-dot-chain line). Note that the case in which the adjustment circuit **153** was short-circuited is the case in which the ground plane **50** and the metal plate **120** were connected by the connection line **133** as depicted in FIG. **4** without insertion of the adjustment circuit **153**.

As compared with the case in which the adjustment circuit **153** was short-circuited, the 1.9 GHz band was shifted to a low frequency side when the inductor was inserted, and the 1.9 GHz band was shifted to a high frequency side when the capacitor was inserted. From this, it was confirmed that the resonance frequency is adjustable by inserting the adjustment circuit **153** as an inductor or capacitor into the connection line **133**.

Also, it was confirmed from this that the resonance frequency is adjustable by inserting the adjustment circuit **153** without changing the position of the connection line **133** to the Y axis direction. For example, when the position of the connection line **133** is limited due to the positional relation with a circuit component included in the electronic device or the like, the use of the adjustment circuit **153** allows impedance matching at a desired resonance frequency.

Also, while the above description has been made by using the wavelengths **1**, **2**, **3**, **4**, and **5** of basic waves of the frequencies **f1**, **f2**, **f3**, **f4**, and **f5**, communications at the frequencies **f1**, **f2**, **f3**, **f4**, and **f5** may be made possible by setting so that the wavelengths of harmonics of orders equal to or higher than the second order at the frequencies **f1**, **f2**, **f3**, **f4**, and **f5** satisfy the above-described conditions.

While the antenna device and the wireless communication device of the exemplary embodiment of the present invention has been described above, the present invention is not limited to the specifically disclosed embodiment and may be variously modified or changed without deviating from the scope of the claims.

The following appendices are further disclosed regarding the above-described embodiment.

(Appendix 1)

An antenna device including:

- a ground plane which has an edge side;
- a metal member arranged along the edge side of the ground plane;

a first connection line which connects the metal member and the ground plane;

a second connection line which connects the metal member and the ground plane; and

- a power feeding element which has a power feeding point, extends along the metal member from the power feeding point between the first connection line and the second connection line, and is electromagnetic-field-coupled to the metal member.

(Appendix 2)

The antenna device according to appendix 1, in which

- a length of the metal member between the first connection line and the second connection line is a length corresponding to $\frac{1}{2}$ of a first wavelength at a first frequency and is a length corresponding to a second wavelength at a second frequency which is a double of the first frequency.

(Appendix 3)

The antenna device according to appendix 2, in which

- a first loop constructed of the metal member, the first connection line, the second connection line, and the ground plane constructs a loop antenna which resonates at the first frequency and the second frequency.

(Appendix 4)

The antenna device according to appendix 2 or 3, in which

- a length of the power feeding element is longer than 0.07 times of a length of a wavelength at the second frequency and shorter than 0.2 times of the length of the wavelength at the second frequency.

(Appendix 5)

The antenna device according to any one of appendices 1 to 4, further including:

- an inductor or capacitor loaded on the second connection line.

(Appendix 6)

The antenna device according to any one of appendices 1 to 5, further including:

- a third connection line which connects the metal member and the ground plane oppositely to the second connection line with respect to the first connection line.

(Appendix 7)

The antenna device according to appendix 6, further including:

- an inductor or capacitor loaded on the third connection line.

(Appendix 8)

The antenna device according to appendix 6 or 7, in which

- a length of the metal member between the first connection line and the third connection line is a length corresponding to $\frac{1}{2}$ of a third wavelength at a third frequency.

(Appendix 9)

The antenna device according to appendix 8, in which

- a second loop constructed of the metal member, the first connection line, the third connection line, and the ground plane constructs a loop antenna which resonates at the third frequency.

(Appendix 10)

The antenna device according to any one of appendices 1 to 9, in which

- a distance between a position corresponding to the power feeding point on the edge side of the ground plane and a position where the first connection line is connected to the ground plane is set at a distance represented by a length corresponding to $\frac{1}{2}$ of a fourth wavelength in a fourth frequency.

(Appendix 11)

The antenna device according to any one of appendices 1 to 10, further including:

a branch element which is connected to the power feeding element at the power feeding point, extends from the power feeding point to a direction opposite to the power feeding element along the metal member, and has a length corresponding to $\frac{1}{4}$ of a wavelength at a fifth frequency.

(Appendix 12)

A wireless communication device including:

a substrate; and

an antenna device disposed on the substrate, in which the antenna device includes

a ground plane which has an edge side,

a metal member arranged along the edge side of the ground plane,

a first connection line which connects the metal member and the ground plane,

a second connection line which connects the metal member and the ground plane, and

a power feeding element which has a power feeding point, extends along the metal member from the power feeding point between the first connection line and the second connection line, and is electromagnetic-field-coupled to the metal member.

All examples and conditional language provided herein are intended for the pedagogical purposes of aiding the reader in understanding the invention and the concepts contributed by the inventor to further the art, and are not to be construed as limitations to such specifically recited examples and conditions, nor does the organization of such examples in the specification relate to a showing of the superiority and inferiority of the invention. Although one or more embodiments of the present invention have been described in detail, it should be understood that the various changes, substitutions, and alterations could be made hereto without departing from the spirit and scope of the invention.

What is claimed is:

1. An antenna device comprising:

a ground plane which has an edge side;

a metal member arranged along the edge side of the ground plane;

a first connection line which couples the metal member and the ground plane;

a second connection line which couples the metal member and the ground plane; and

a power feeding element which has a power feeding point which is not physically in contact with the metal member, extends in parallel with the metal member from the power feeding point between the first connection line and the second connection line, keeps a specific distance from the metal member, includes the power feeding point and an open end at respective ends of the power feeding element and is electromagnetic-field-coupled to the metal member,

wherein the power feeding point is coupled to a substrate including the ground plane via an elastic member which extends in a vertical direction of a surface of the substrate, and the antenna device performs communication in four or more frequency bands which are different from each other.

2. The antenna device according to claim 1, further comprising:

an inductor or capacitor loaded on the second connection line.

3. The antenna device according to claim 1, further comprising:

a third connection line which couples the metal member and the ground plane oppositely to the second connection line with respect to the first connection line.

4. The antenna device according to claim 3, further comprising:

an inductor or capacitor loaded on the third connection line.

5. The antenna device according to claim 3, wherein a length of the metal member between the first connection line and the third connection line is a length corresponding to $\frac{1}{2}$ of an electrical length of a third wavelength at a third frequency which is one frequency having radiation characteristic with less reflection than other frequencies in frequency characteristic of the antenna device.

6. The antenna device according to claim 5, wherein a second loop constructed of the metal member, the first connection line, the third connection line, and the ground plane constructs a loop antenna which resonates at the third frequency.

7. The antenna device according to claim 1, wherein a distance between a position corresponding to the power feeding point on the edge side of the ground plane and a position where the first connection line is connected to the ground plane is set at a distance represented by a length corresponding to $\frac{1}{2}$ of an electrical length of a fourth wavelength in a fourth frequency which is one frequency having radiation characteristic with less reflection than other frequencies in frequency characteristic of the antenna device.

8. The antenna device according to claim 1, further comprising:

a branch element which is coupled to the power feeding element at the power feeding point, extends from the power feeding point to a direction opposite to the power feeding element along the metal member, and has a length corresponding to $\frac{1}{4}$ of an electrical length of a wavelength at a fifth frequency which is one frequency having radiation characteristic with less reflection than other frequencies in frequency characteristic of the antenna device.

9. A wireless communication device comprising:

a substrate; and

an antenna device disposed on the substrate, wherein the antenna device includes:

a ground plane which has an edge side;

a metal member arranged along the edge side of the ground plane;

a first connection line which couples the metal member and the ground plane;

a second connection line which couples the metal member and the ground plane; and

a power feeding element which has a power feeding point which is not physically in contact with the metal member, extends in parallel with the metal member from the power feeding point between the first connection line and the second connection line, keeps a specific distance from the metal member, includes the power feeding point and an open end at respective ends of the power feeding element and is electromagnetic-field-coupled to the metal member, wherein the power feeding point is coupled to the substrate via an elastic member which extends in a vertical direction of a surface of the substrate, and

the antenna device performs communication in four or more frequency bands which are different from each other.

10. The wireless communication device according to claim 9, wherein the antenna device further includes an inductor or capacitor loaded on the second connection line. 5

11. The wireless communication device according to claim 9, wherein the antenna device further includes a third connection line which couples the metal member and the ground plane oppositely to the second connection line with respect to the first connection line. 10

12. The wireless communication device according to claim 11, wherein the antenna device further includes an inductor or capacitor loaded on the third connection line.

13. The wireless communication device according to claim 9, wherein a distance between a position corresponding to the power feeding point on the edge side of the ground plane and a position where the first connection line is connected to the ground plane is set at a distance represented by a length corresponding to $\frac{1}{2}$ of an electrical length of a fourth wavelength in a fourth frequency. 15 20

14. The wireless communication device according to claim 9, further comprising:

a branch element which is coupled to the power feeding element at the power feeding point, extends from the power feeding point to a direction opposite to the power feeding element along the metal member, and has a length corresponding to $\frac{1}{4}$ of an electrical length of a wavelength at a fifth frequency which is one frequency having radiation characteristic with less reflection than other frequencies in frequency characteristic of the antenna device. 25 30

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